Characterization Techniques for Identifying Hydraulically Active Fractures in Sedimentary Rocks

Dr. Beth Parker
School of Engineering, University of Guelph

MGWA Spring 2012 Conference
Conduits, Karst, and Contamination
Addressing Groundwater Challenges
April 19, 2012

Acknowledgements

- Funding
  - Natural Sciences and Engineering Research Council of Canada (NSERC)
  - Canada Foundation for Innovations (CFI)
  - Ontario Ministry of Research and Innovation (MRI)
  - University Consortium for Field-Focused Groundwater Research sponsors
  - Groundwater Equipment Companies

- **Collaborators:** Drs. John Cherry, T. Gorecki, and R. Aravena, E.Sudicky, J. Molson, and others

- Many research associates, technicians and students:
  - Chapman, Meyer, Pehme, Quinn, Munn and others

- Site owners, consultants and regulators

Contact Information

Beth Parker

Email: bparker@uoguelph.ca

Phone: (519) 824-4120 x53642

References

Goldstein, K.J., A.R. Vitolins, D. Navon, B.L. Parker, S.W. Chapman, and G.A. Anderson. 2004. Characterization and pilot-scale studies for chemical oxidation remediation of fractured shale. *Remediation* 14, no.4: 19-37.

Munn, J.D. 2011. High-resolution discrete fracture network characterization using inclined coreholes in a Silurian dolostone aquifer in Guelph, Ontario. Master's thesis, Land Resource Science, University of Guelph.

Parker, B.L., J.A. Cherry, and S.W. Chapman. 2011. Advances in the DFN Approach for investigating contaminated sites on fractured sedimentary rock. In *Proceedings 2011 NGWA Focus Conference on Fractured Rock and Eastern Groundwater Regional Issues, September 26-27, 2011, Burlington, Vermont*, Westerville, Ohio: National Ground Water Association.

Pehme, P.E., J.P. Greenhouse, and B.L. Parker. 2007. The active line source (ALS) technique, a method to improve detection of hydraulically active fractures and estimate rock thermal conductivity. In *Proceedings, 60th Canadian Geotechnical Conference and 8th Joint CGS/IAH-CNC Groundwater Conference, 21-24 October 2007, Ottawa, ON*, 1-8, Ottawa, Ontario: International Association of Hydrogeologists.

Pehme, P.E., B.L. Parker, J.A. Cherry, and J.P. Greenhouse. 2010. Improved resolution of ambient flow through fractured rock with temperature logs. *Ground Water* 48, no.2: 191-205.

References (cont.)

Quinn, P.M., J.A. Cherry, and B.L. Parker. *submitted October 2011*. Hydraulic testing using a versatile straddle packer system for improved transmissivity estimation in fractured rock boreholes. *submitted to Hydrogeology Journal.*

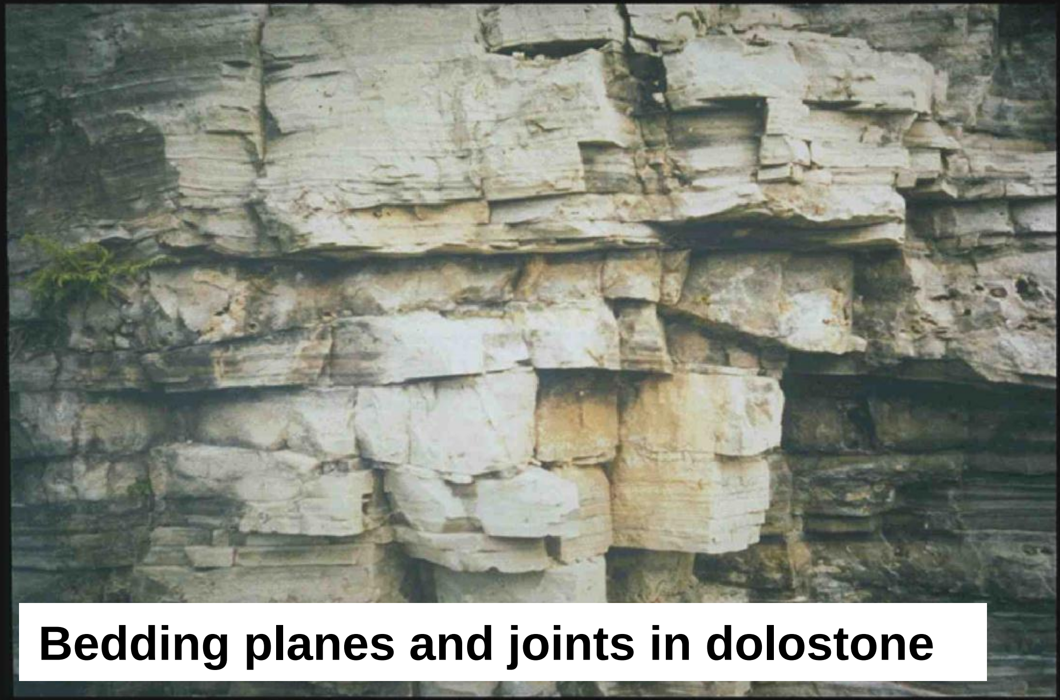
Quinn, P.M., J.A. Cherry, and B.L. Parker. 2011a. Quantification of non-Darcian flow observed during packer testing in fractured sedimentary rock. *Water Resources Research* 47, no.9: W09533

Quinn, P.M., B.L. Parker, and J.A. Cherry. 2011b. Using constant head step tests to determine hydraulic apertures in fractured rock. *Journal of Contaminant Hydrology* 126, no.1-2: 85-99.

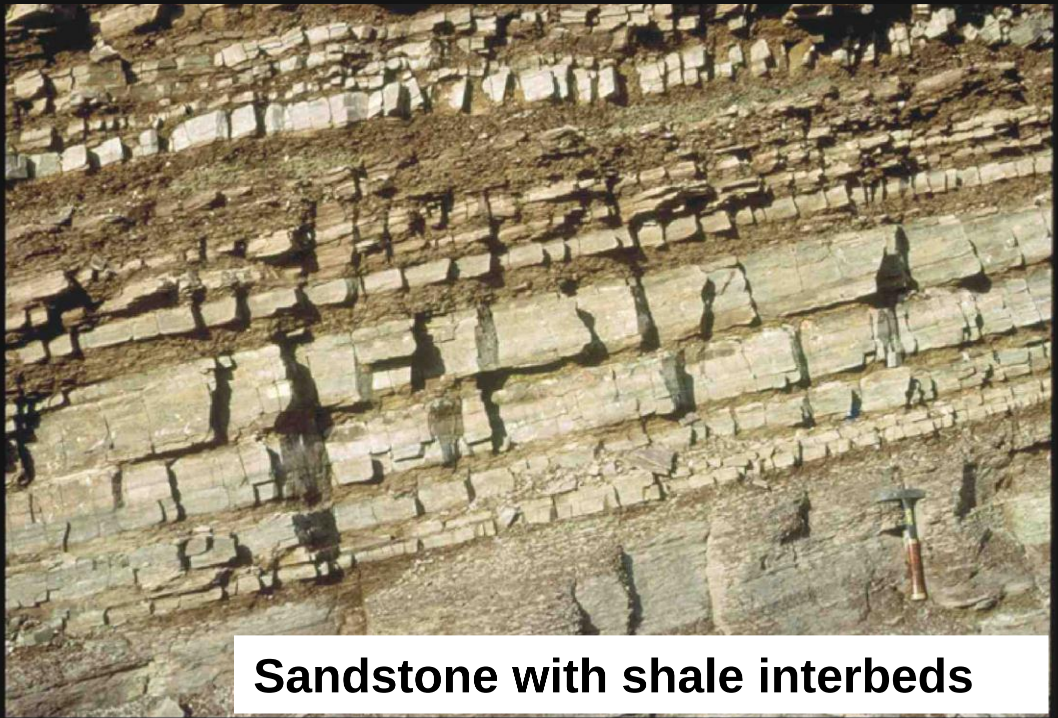
Sterling, S.N., B.L. Parker, J.A. Cherry, J.H. Williams, J.W. Lane Jr., and F.P. Haeni. 2005. Vertical cross contamination of trichloroethylene in a borehole in fractured sandstone. *Ground Water* 43, no.4: 557-573.

Williams, J.H. and F.L. Paillet. 2002. Using flowmeter pulse tests to define hydraulic connections in the subsurface: a fractured shale example. *Journal of Hydrology* 265: 100–117.

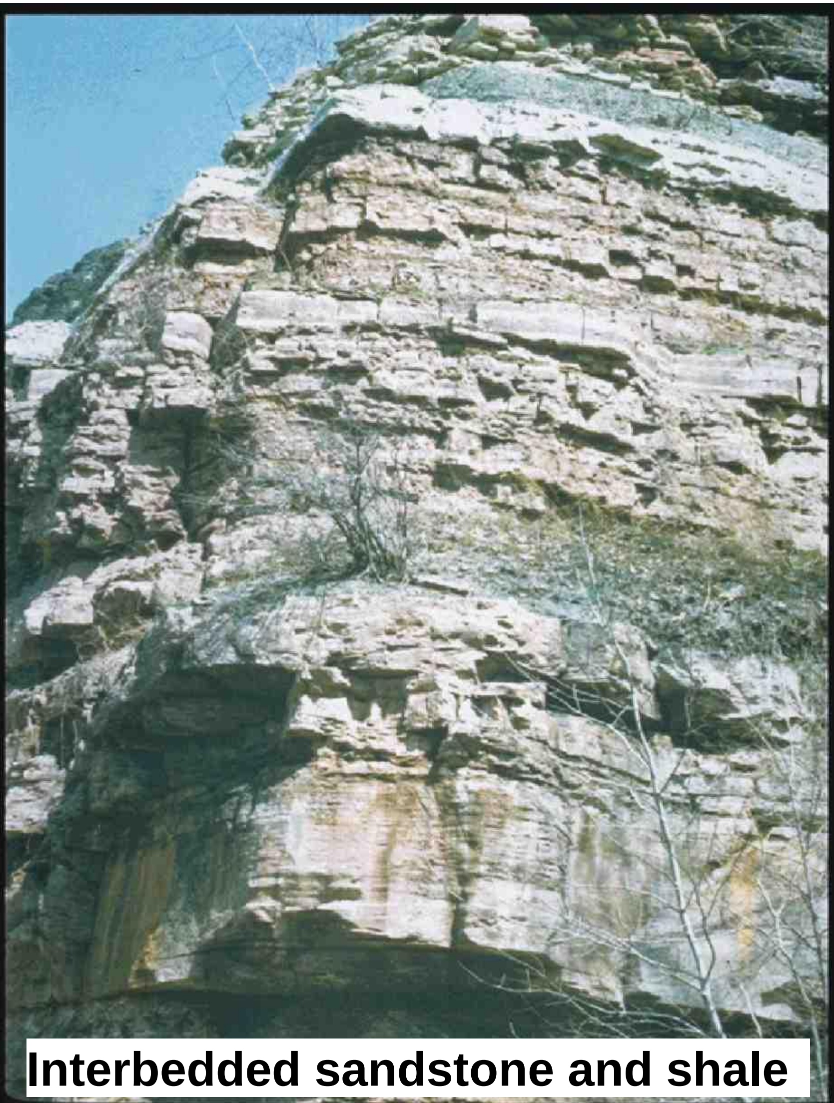
Fractured Porous Media



Bedding planes and joints in dolostone



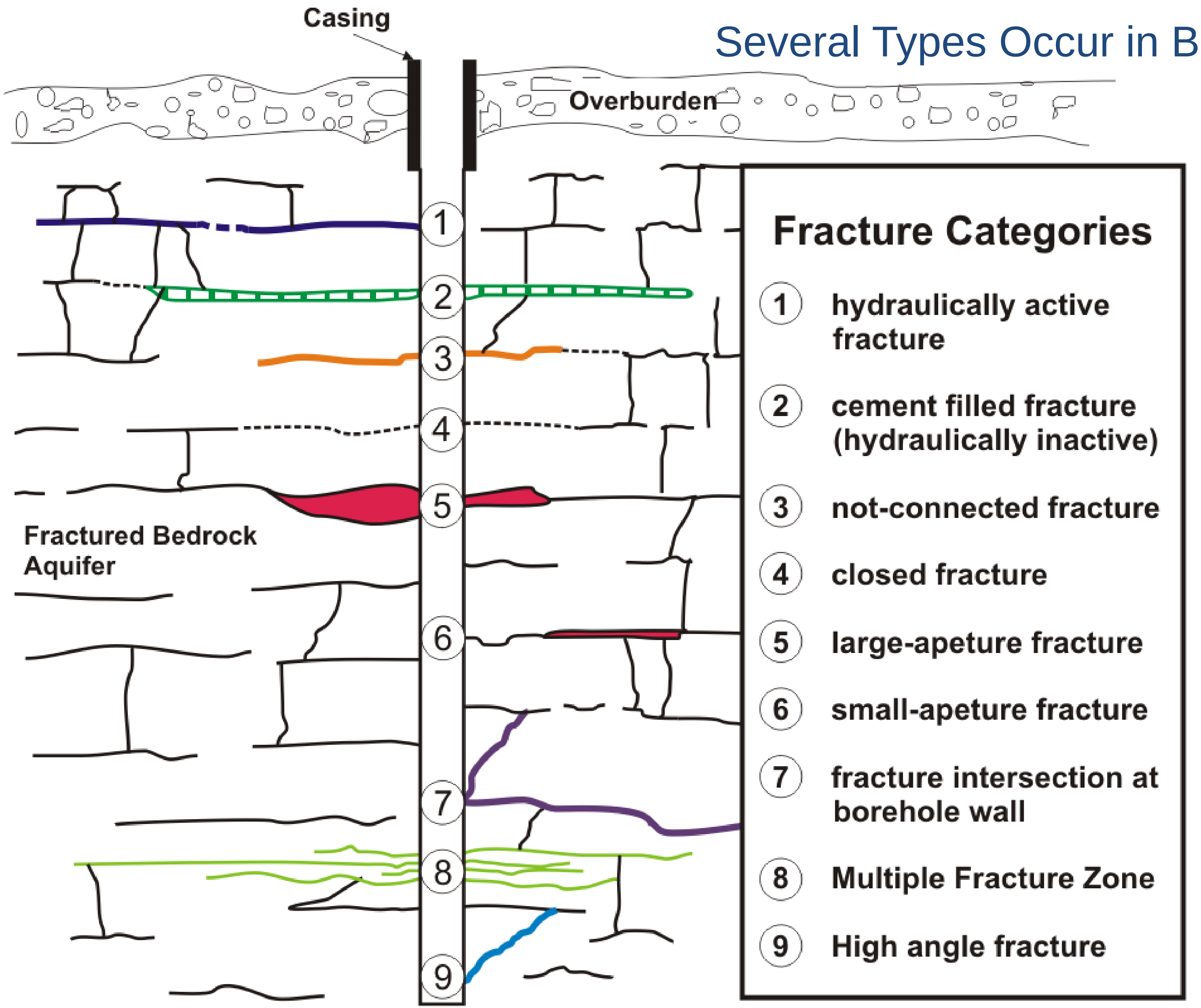
Sandstone with shale interbeds



Interbedded sandstone and shale

"Borehole Fractures"

Several Types Occur in Boreholes



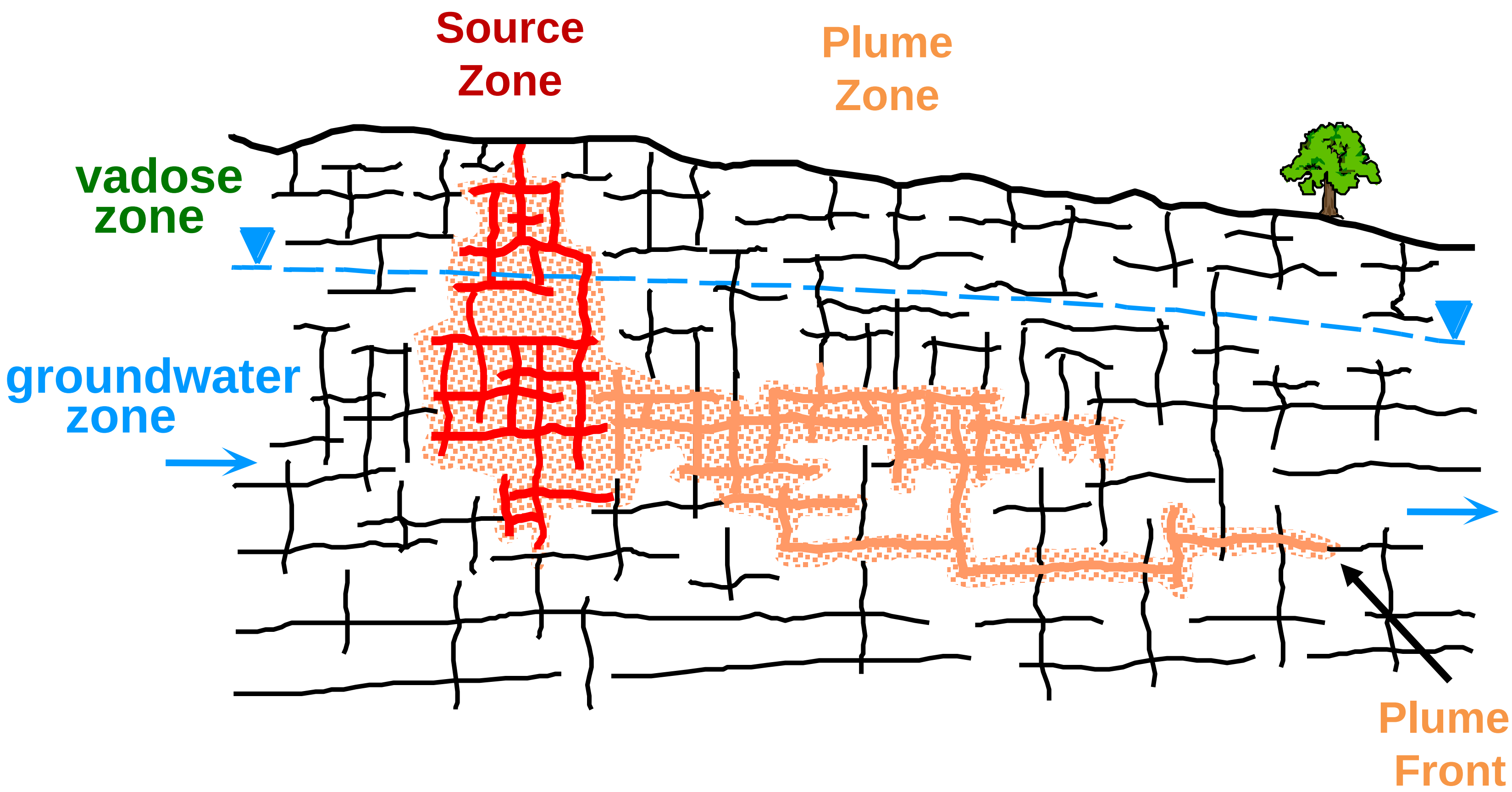
How can we identify each type?

The amount of land involved in a wellhead protection area is determined by a variety of factors including…

the speed that groundwater travels, which depends on fracture aperture

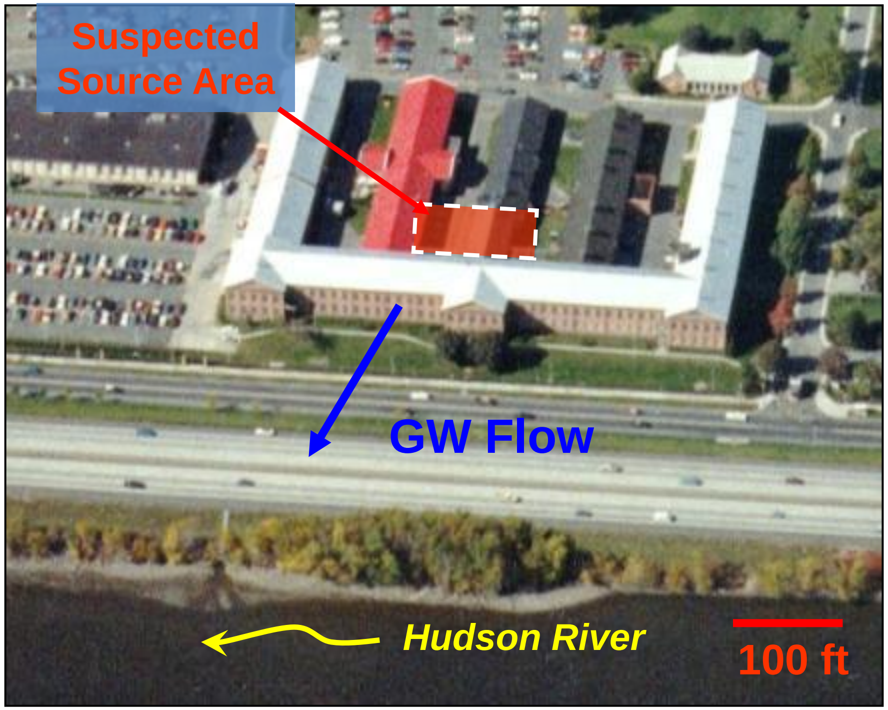
Nature of Contamination in Fractured Sedimentary Rock

Requires a Different Approach



New York State Site
Watervliet Arsenal Site: Building 40

- **Suspected degreaser source**
  - releases 1950s-60s
- **PCE and degradation products**
- **Depth to shale bedrock ~ 15-20 ft bgs**
- **Contamination down to ~ 200 ft bgs**
- **Plume discharges to Hudson River**



Fracture Network Conceptual Model from Borehole Flow Tests

- Results from USGS Study 2000-01
- Published in Journal of Hydrology 2002
- Tests in open boreholes

ELSEVIER

Journal of Hydrology 265 (2002) 100–117

Journal of Hydrology

www.elsevier.com/locate/jhydrol

Using flowmeter pulse tests to define hydraulic connections in the subsurface: a fractured shale example

J.H. Williams[a], F.L. Paillet[b,*]

[a]United States Geological Survey, 425 Jordan Road, Troy, NY 12180, USA
[b]United States Geological Survey, Borehole Geophysics Research Project, Box 25046, MS 403, Denver, CO 80225, USA

Received 31 October 2001; revised 01 March 2002; accepted 25 April 2002

Abstract

Cross-borehole flowmeter pulse tests define subsurface connections between discrete fractures using short stress periods to monitor the propagation of the pulse through the flow system. This technique is an improvement over other cross-borehole techniques because measurements can be made in open boreholes without packers or previous identification of water-producing intervals. The method is based on the concept of monitoring the propagation of pulses rather than steady flow through the fracture network. In this method, a hydraulic stress is applied to a borehole connected to a single, permeable fracture, and the distribution of flow induced by that stress monitored in adjacent boreholes. The transient flow responses are compared to type curves computed for several different types of fracture connections. The shape of the transient flow response indicates the type of fracture connection, and the fit of the data to the type curve yields an estimate of its transmissivity and storage coefficient. The flowmeter pulse test technique was applied in fractured shale at a volatile-organic contaminant plume in Watervliet, New York. Flowmeter and other geophysical logs were used to identify permeable fractures in eight boreholes in and near the contaminant plume using single-borehole flow measurements. Flowmeter cross-hole pulse tests were used to identify connections between fractures detected in the boreholes. The results indicated a permeable fracture network connecting many of the individual boreholes, and demonstrated the presence of an ambient upward hydraulic-head gradient throughout the site. Published by Elsevier Science B.V.

Keywords: Fractured rock aquifer; Flowmeter logging; Borehole flow modeling

1. Introduction

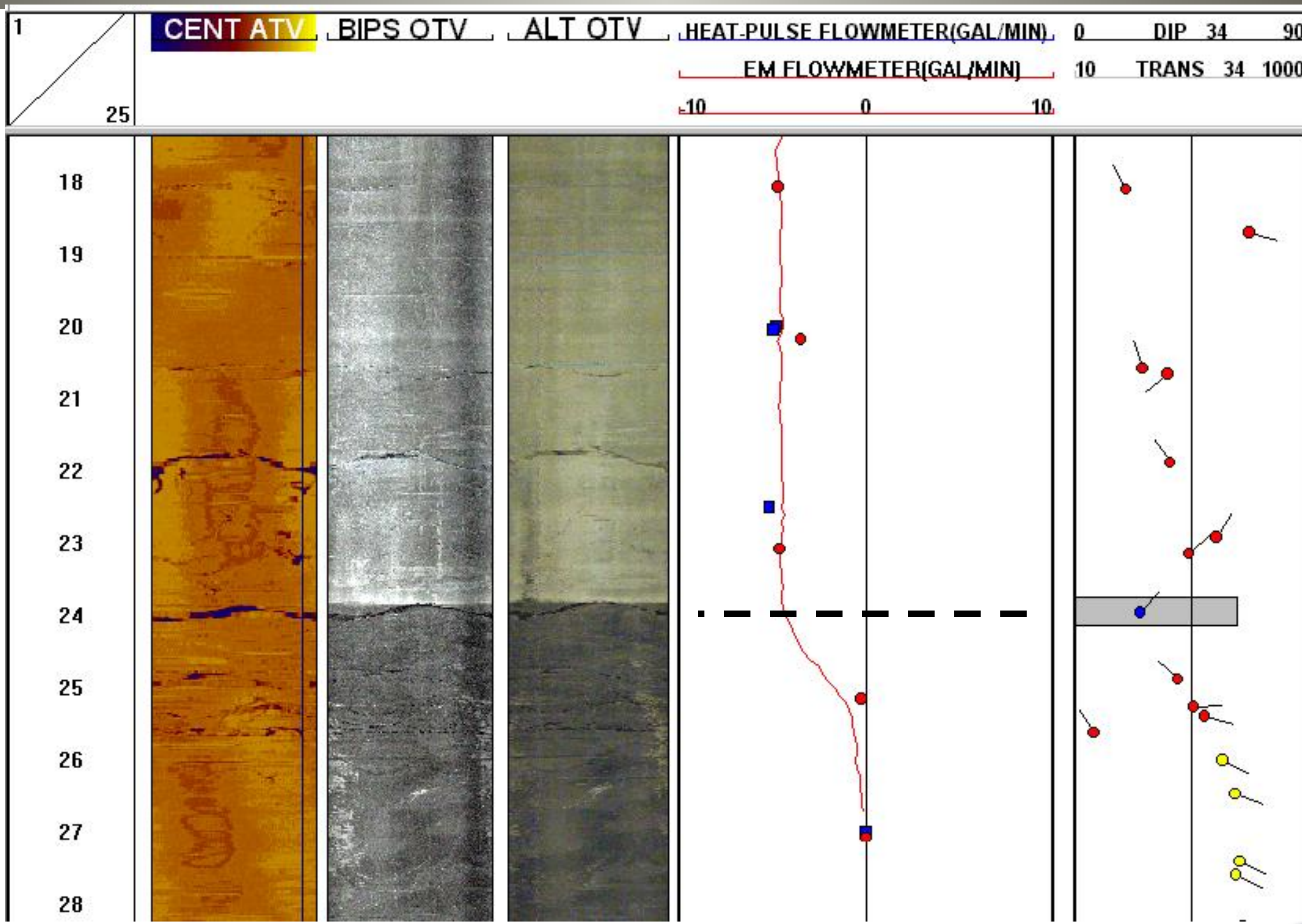
The distribution and migration of contaminants in heterogeneous fractured-rock aquifers is almost impossible to predict on the basis of data from a few individual boreholes. Various down-hole-imaging systems can provide effective samples of fractures and their orientations where those fractures intersect boreholes (Williams and Johnson, 2000). However, numerous studies show that local fracture aperture or fracture density has little if any correlation with fracture permeability (Long et al., 1982; Paillet et al., 1987; Paillet, 1998). Some studies also show that the local orientation of permeable fractures may be very different from the large-scale orientation of the subsurface flow paths to which those fractures are connected (Hardin et al., 1987). Surface-geophysical measurements can, in theory, be used to show how individual sets of fractures identified in boreholes are

* Corresponding author. Present address: Department of Geological Sciences, University of Maine, Orono, ME 04469. Tel: +207-581-3393; Fax: +207-581-2202.

E-mail address: fpaillet@main.edu (F.L. Paillet).

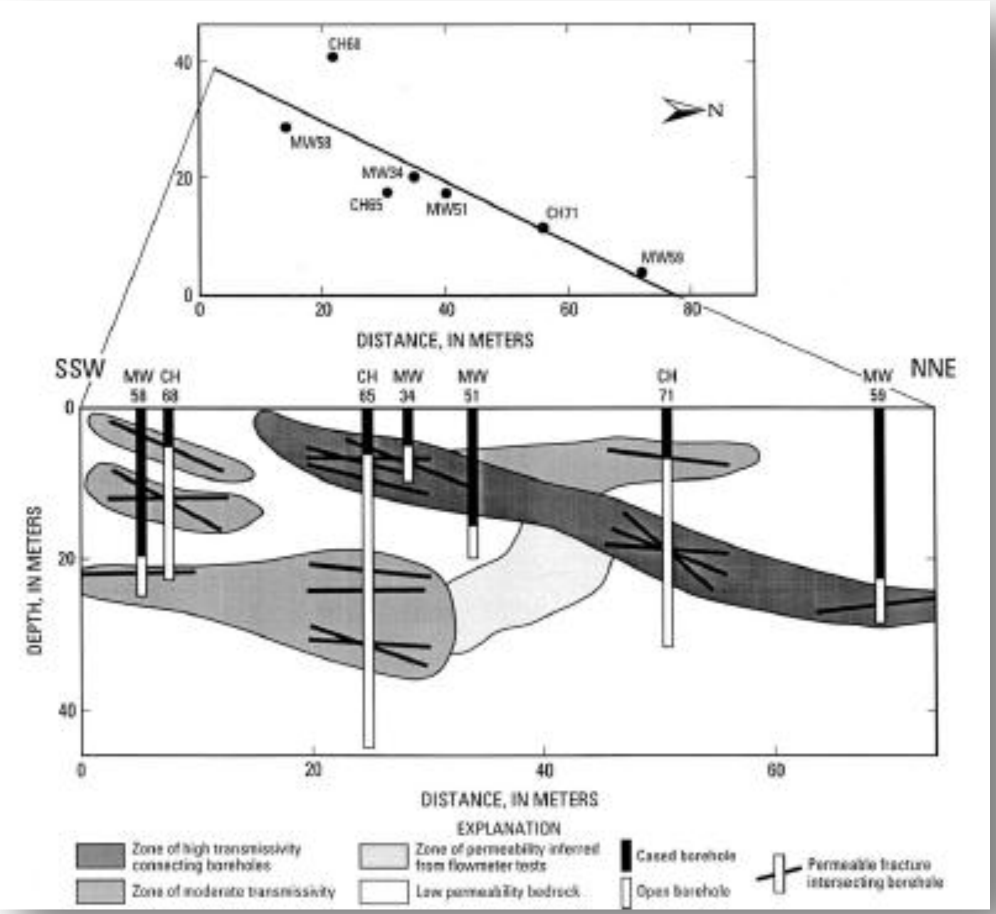
0022-1694/02/$ - see front matter Published by Elsevier Science B.V.
PII: S0022-1694(02)00092-6

One Major Transmissive Zone Identified from BH Flow Logging



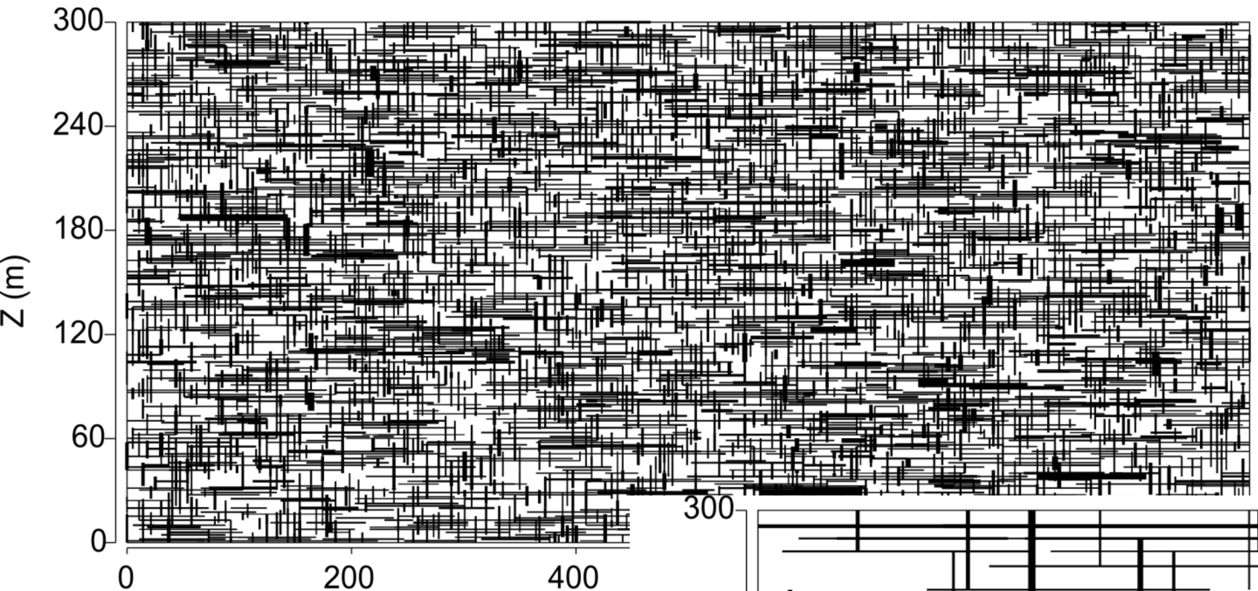
USGS, 2001

Conceptual Model: A Few Large Continuous Fractures or Fracture Zones Dominate



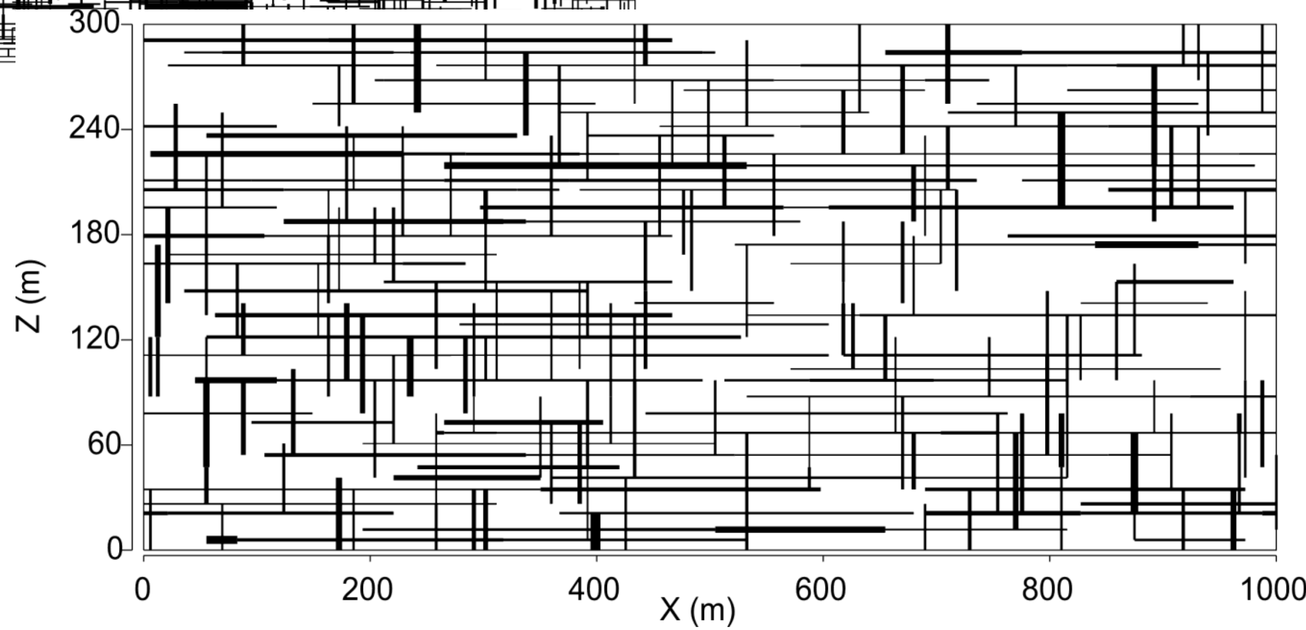
Williams, J.H., Paillet, F.L. 2002. Using flowmeter pulse tests to define hydraulic connections in the subsurface: a fractured shale example. Journal of Hydrology, 265: 100–117.

Key Issues:
How many active fractures?
What is their Interconnectivity?

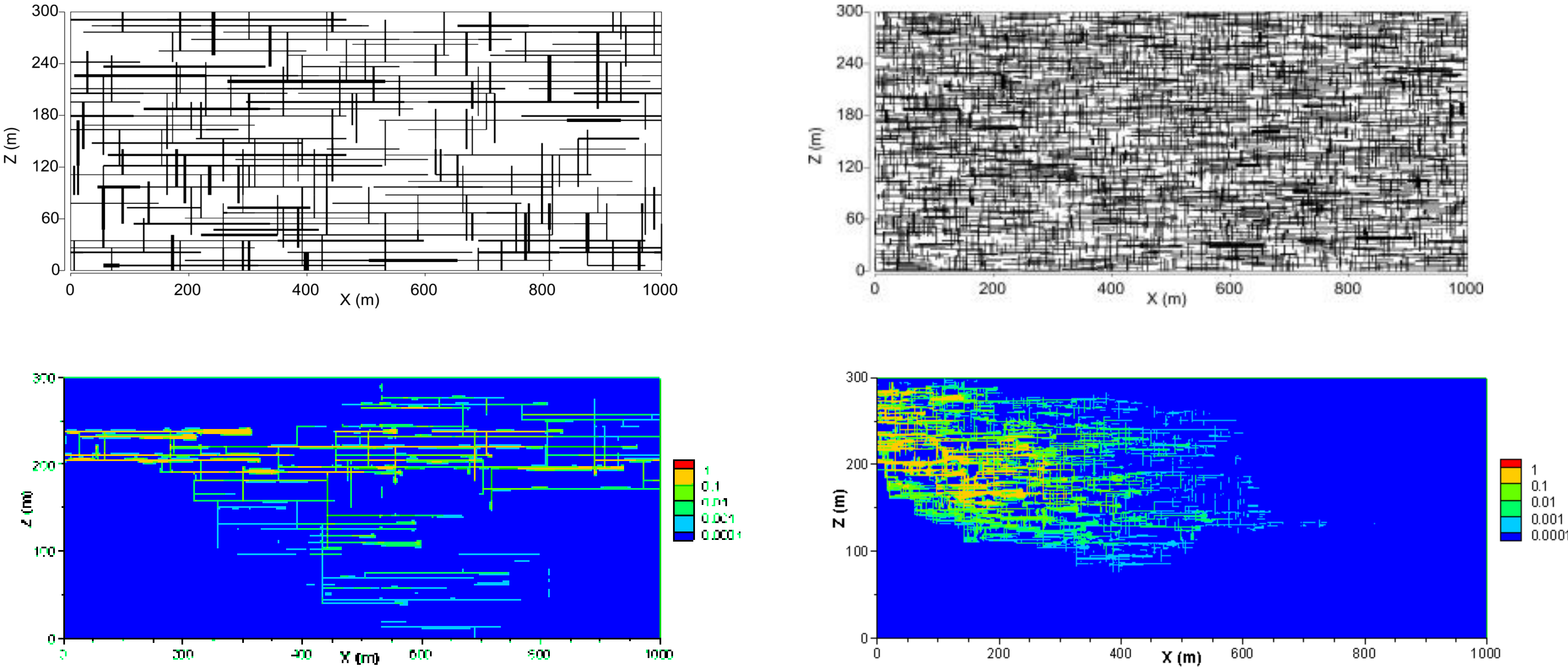


Dense Network

Sparse Network

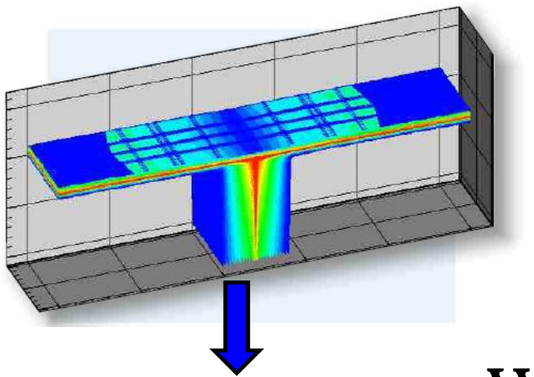


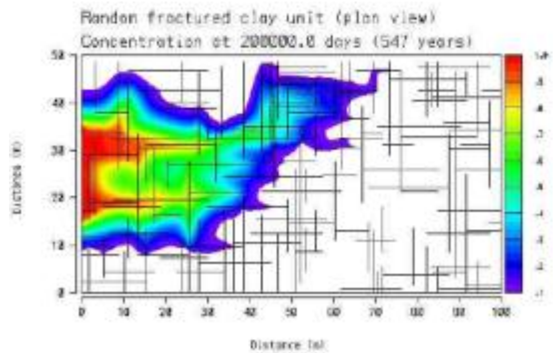
Interplay Between Matrix and Fractures Controls Plume Behavior

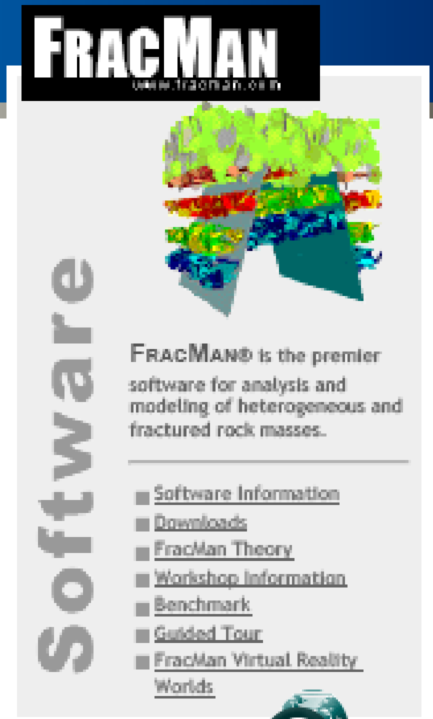


Same bulk K but dissimilar plumes

Commercially Available DFN Models







HydroGeoSphere

HydroGeoSphere
A Three-dimensional Numerical Model Describing Fully-integrated Subsurface and Surface Flow and Solute Transport

R. Therrien, Université Laval
R.G. McLaren, University of Waterloo
E.A. Sudicky, University of Waterloo
S.M. Panday, Hydrogeologic Inc./University of Waterloo

©R. Therrien, E.A. Sudicky, R.G. McLaren
Groundwater Simulations Group

University of Waterloo

Waterloo Hydrogeologic, Inc.
Groundwater is our business

Golder Associates

WASY

360

The Scientific Challenge

Improve understanding and prediction of plume behavior in sedimentary rocks (aquifers and aquitards) to assess risks, remediation designs and response times



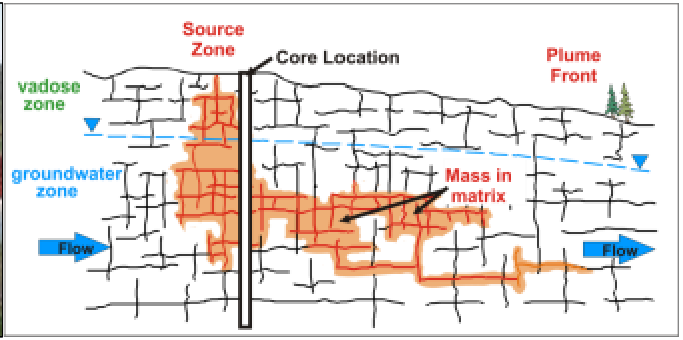
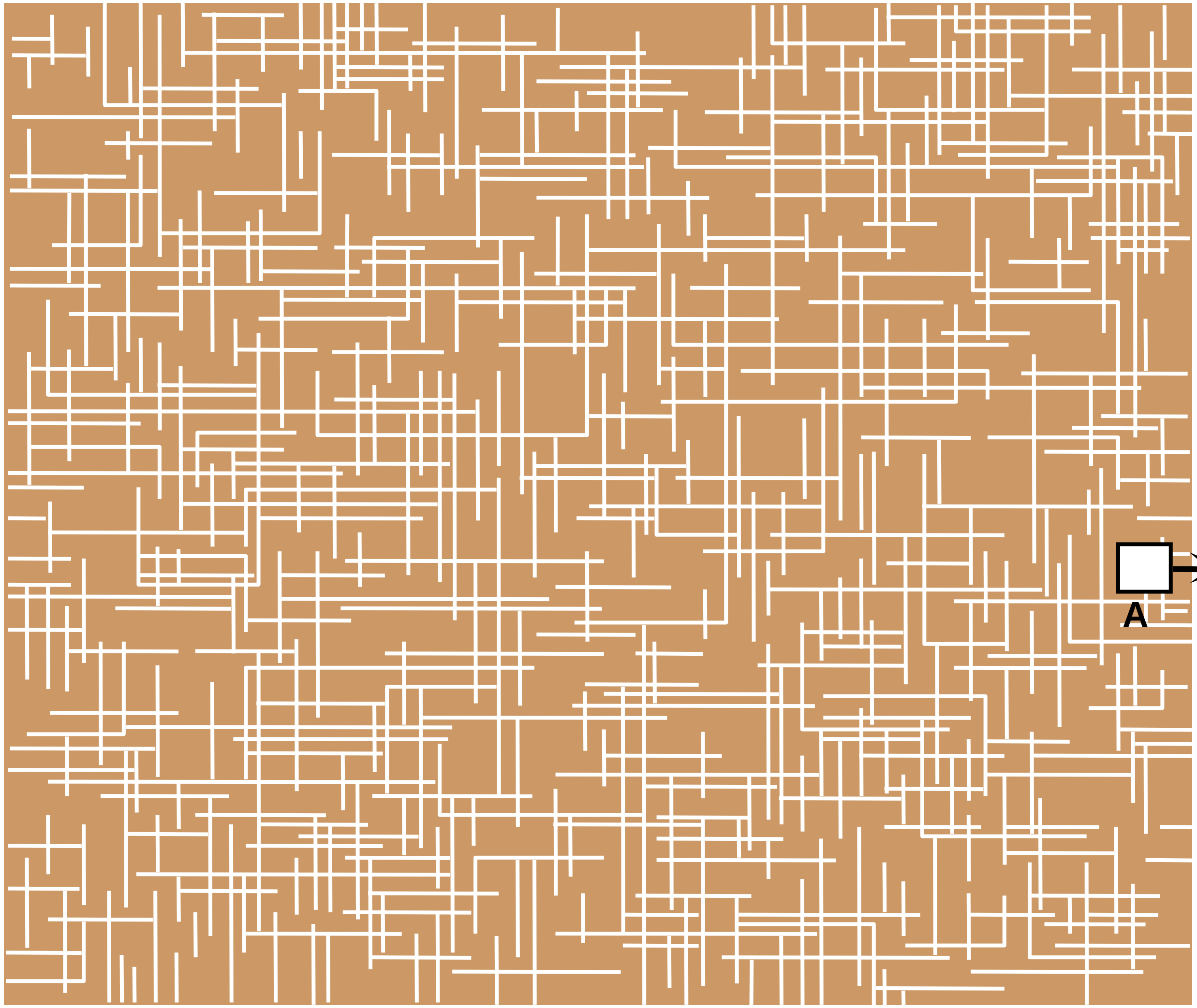


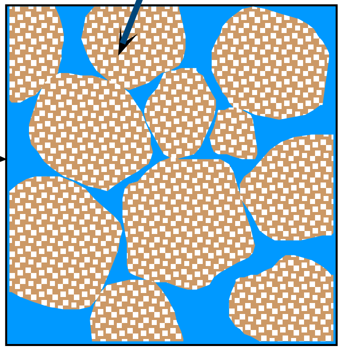

Illustration of Fracture and Matrix Porosities



Matrix Porosity: 2-20%

DETAIL A

mineral particle



Microscopic view of rock matrix

Fracture Porosity: 0.01 to 0.001%

Critical Issues

- Fracture network characteristics
  - Fracture aperture, spacing,
  - length and connectivity
- Matrix properties
  - transport, storage and reactions

Discrete Fracture Network ***Field*** Approach

Use chlorinated solvent plumes as tracers
Natural flow system conditions

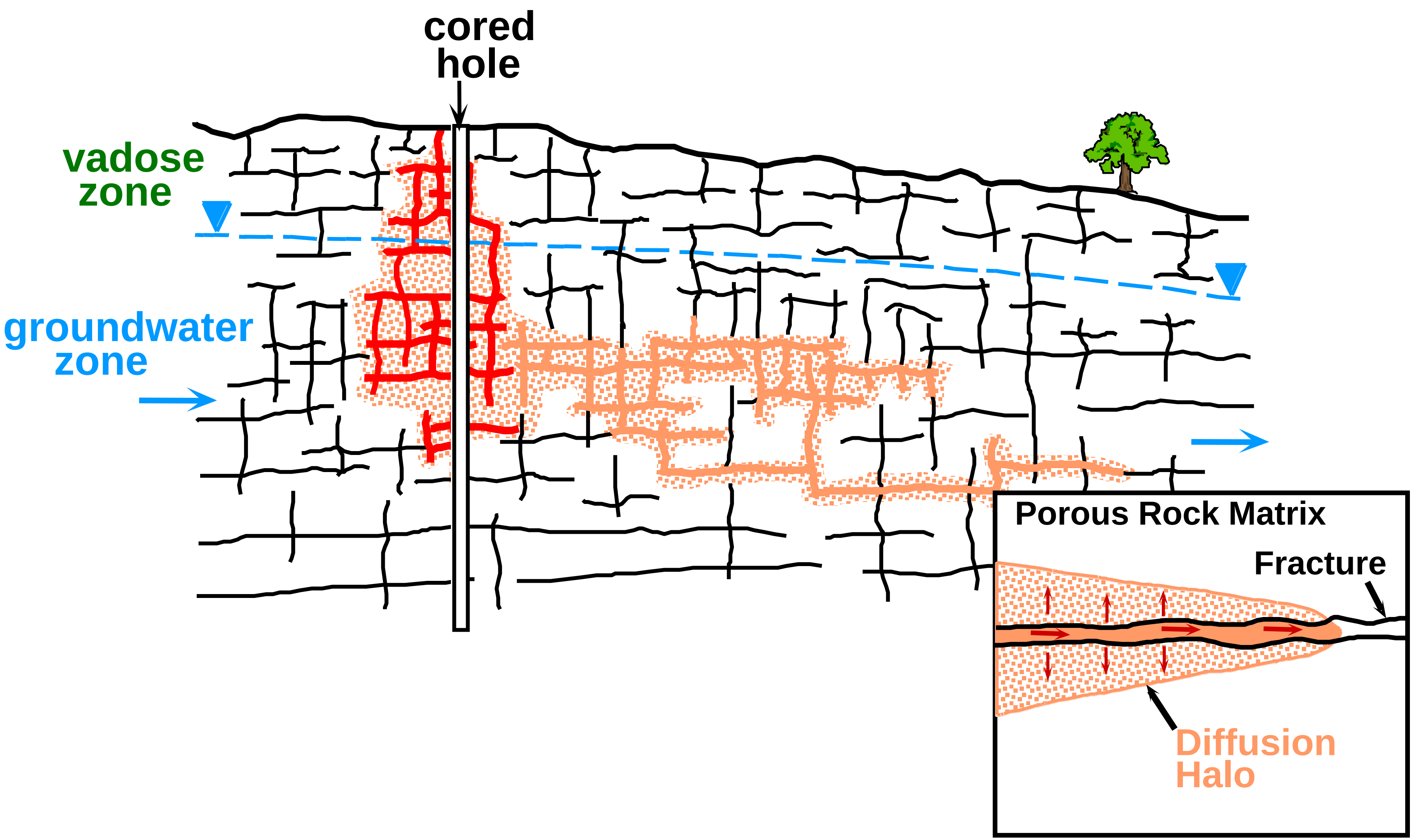
Field Focused Approach

- Revise standard field data collection methods
- Create innovative field data collections methods
- Use field data from contaminated sites to ground-truth conceptual and numerical models

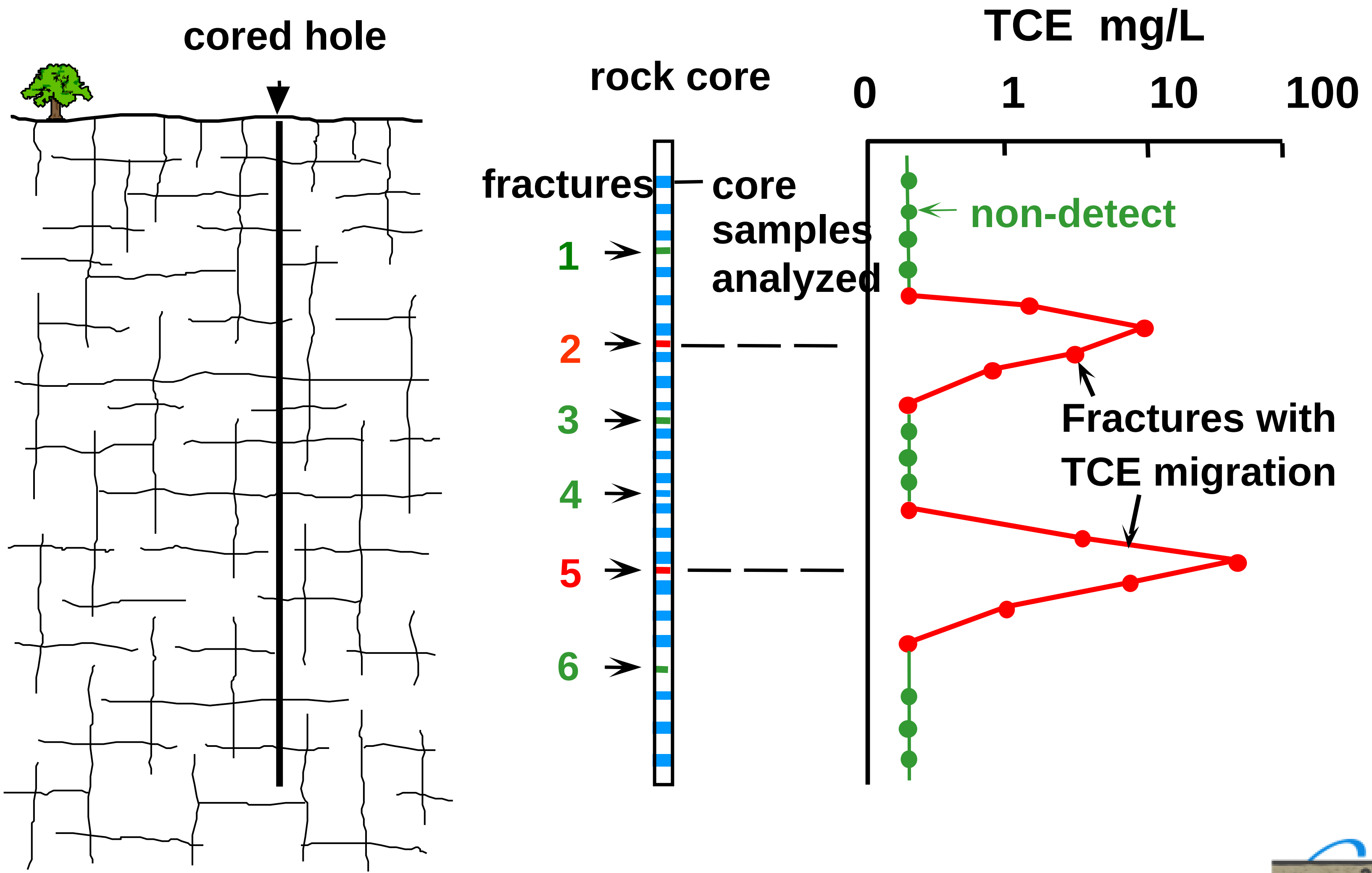
Overview of DFN Methods

- Rock Core Contaminant Analyses & Properties
- Improved Borehole Geophysics
- Improved Hydraulic Tests Using Straddle Packers (Quinn)
- Impermeable Flexible Liner (FLUTe^{TM}) Technologies
- High Resolution Temperature Logging (Pehme et al.)
- Passive Flux Meters (UF/UoG patent)
- High Resolution Multilevel Systems
  - Characterization vs. Monitoring
- Static and Dynamic DFN Modeling

Conceptual Model for Contaminant Distribution

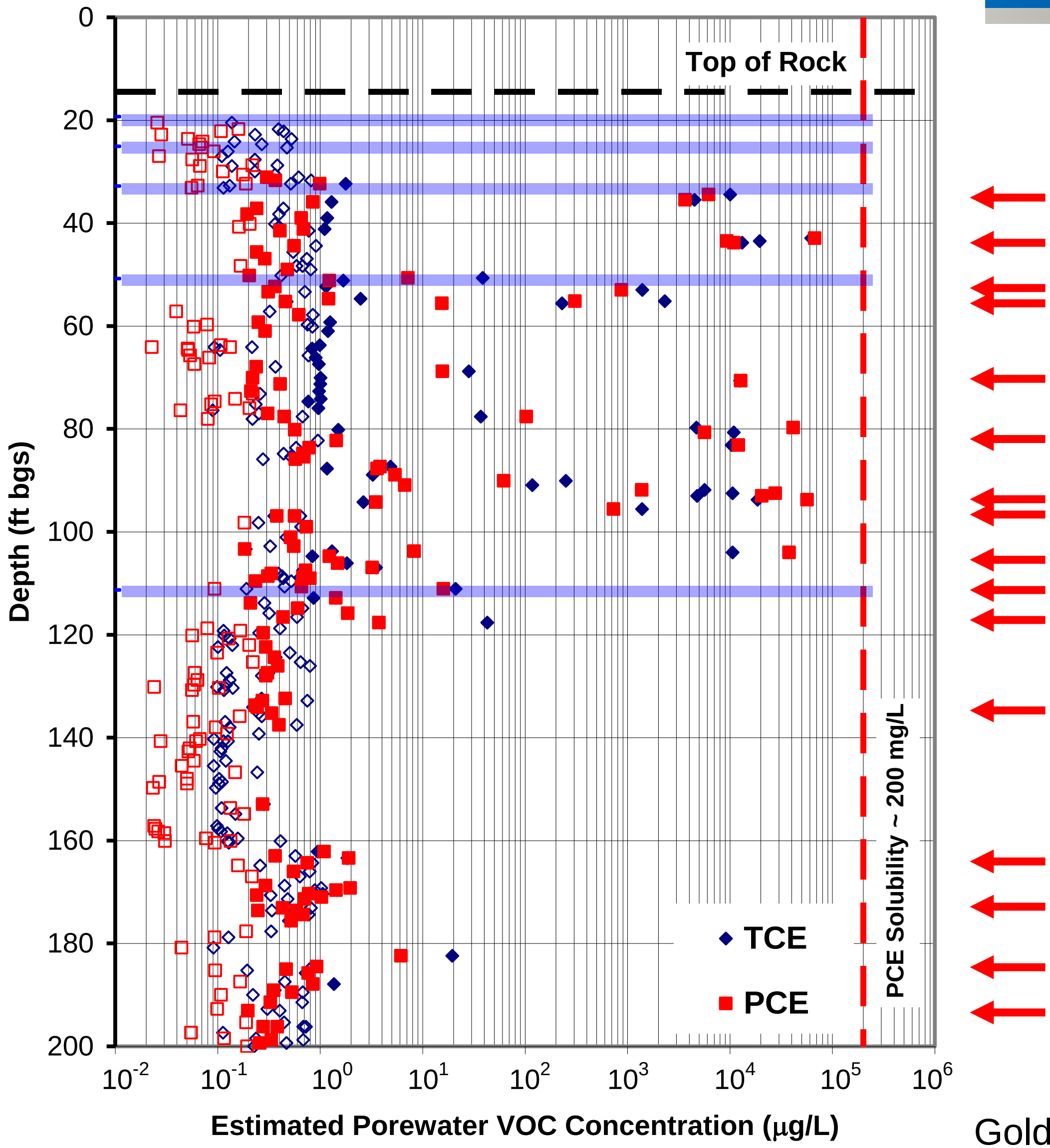


Core Sampling for Mass Distribution



Rock Core VOC Profile versus Flow Zones

MW-83 Oct. 2003



FLOW ZONE VIA HYDROGEOPHYSICAL TESTING

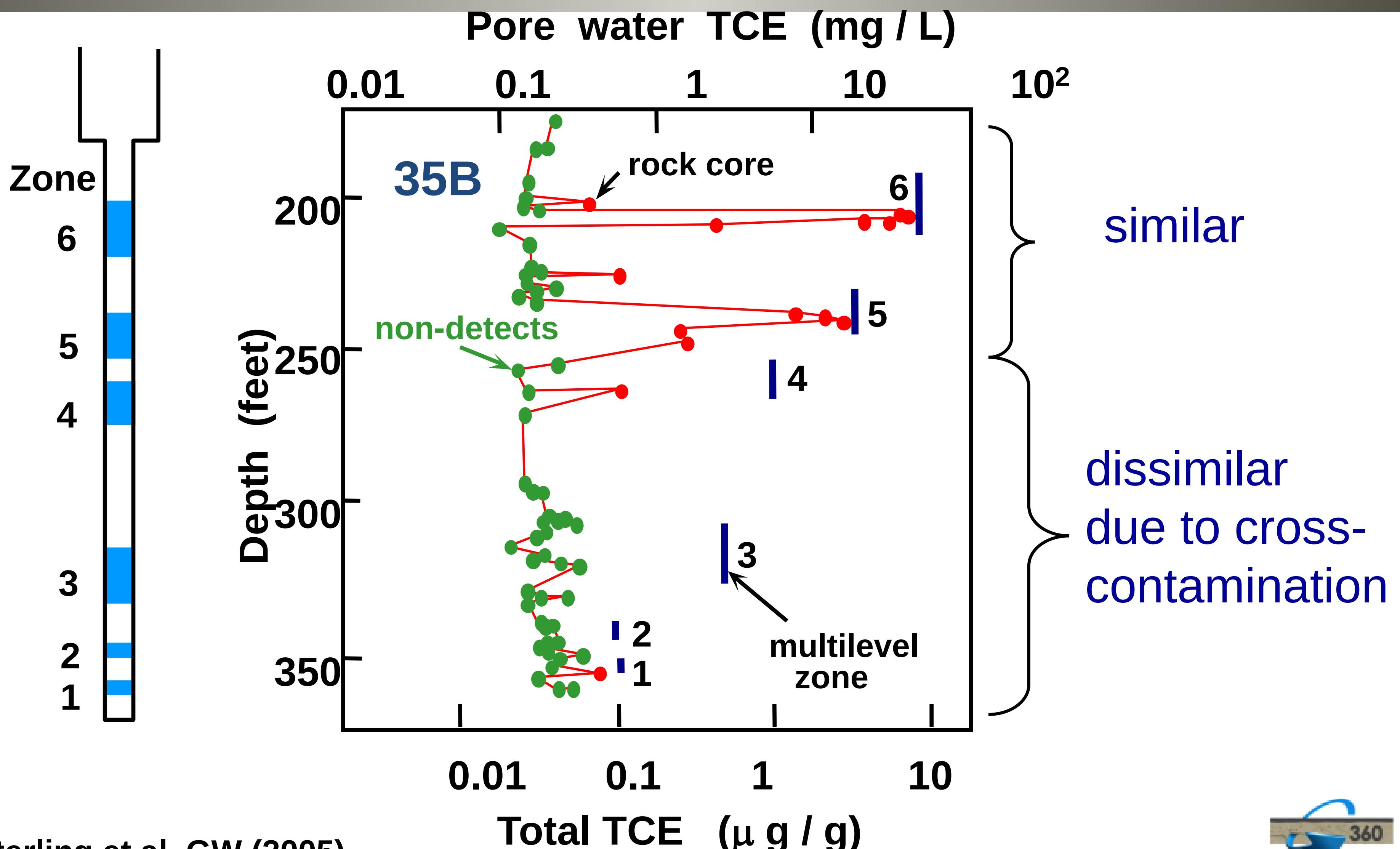
VOC PATHWAY FROM ROCK CORE SAMPLING

Hydrogeophysical Tests Suggest a few Major Flow Zones

Rock Core Indicates Many Fracture Pathways

Goldstein et al. 2004

Comparison of Multilevel and Rock Core Data

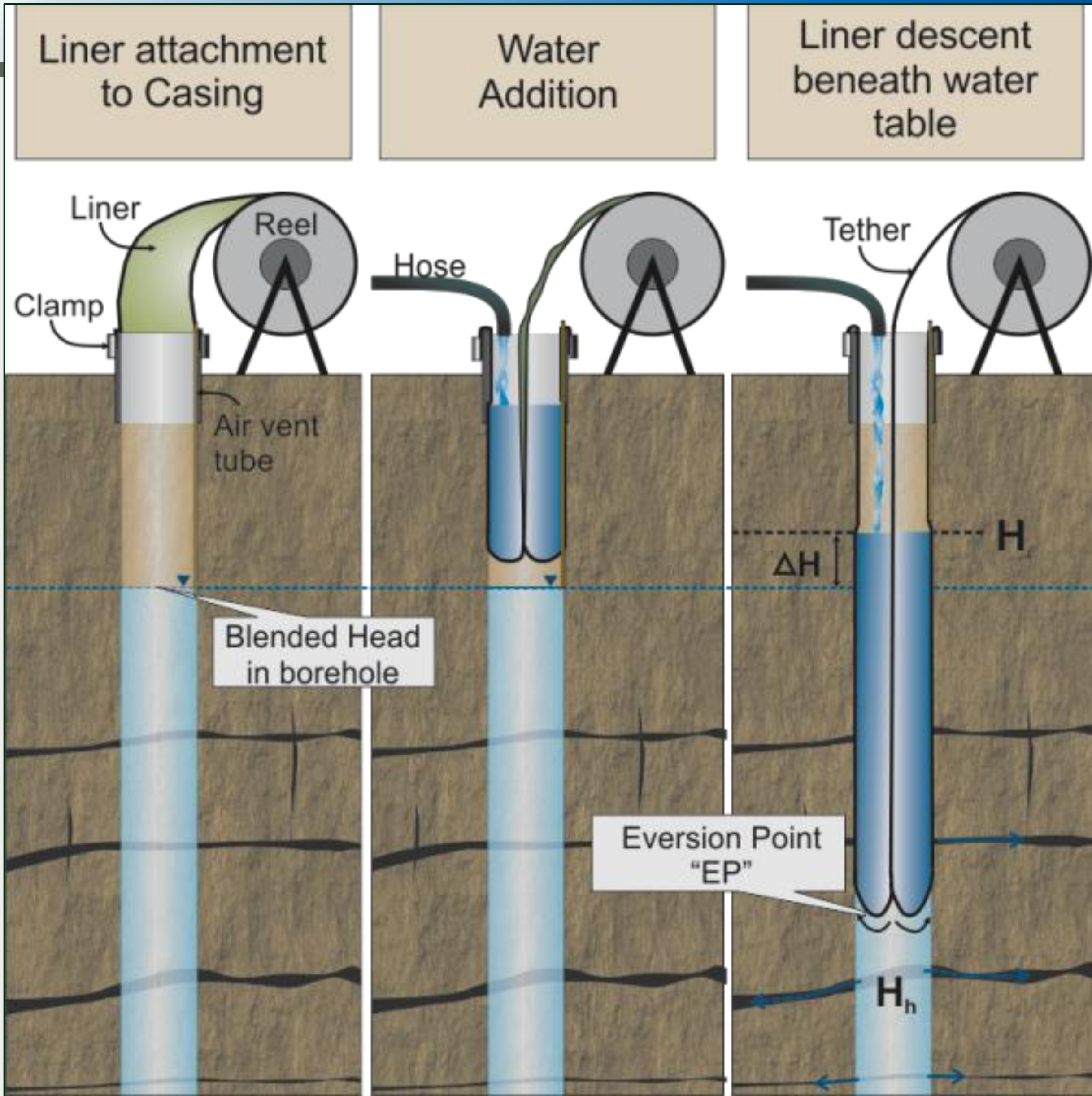


Sterling et al. GW (2005)

FLUTe Liner
Urethane Coated Nylon Fabric

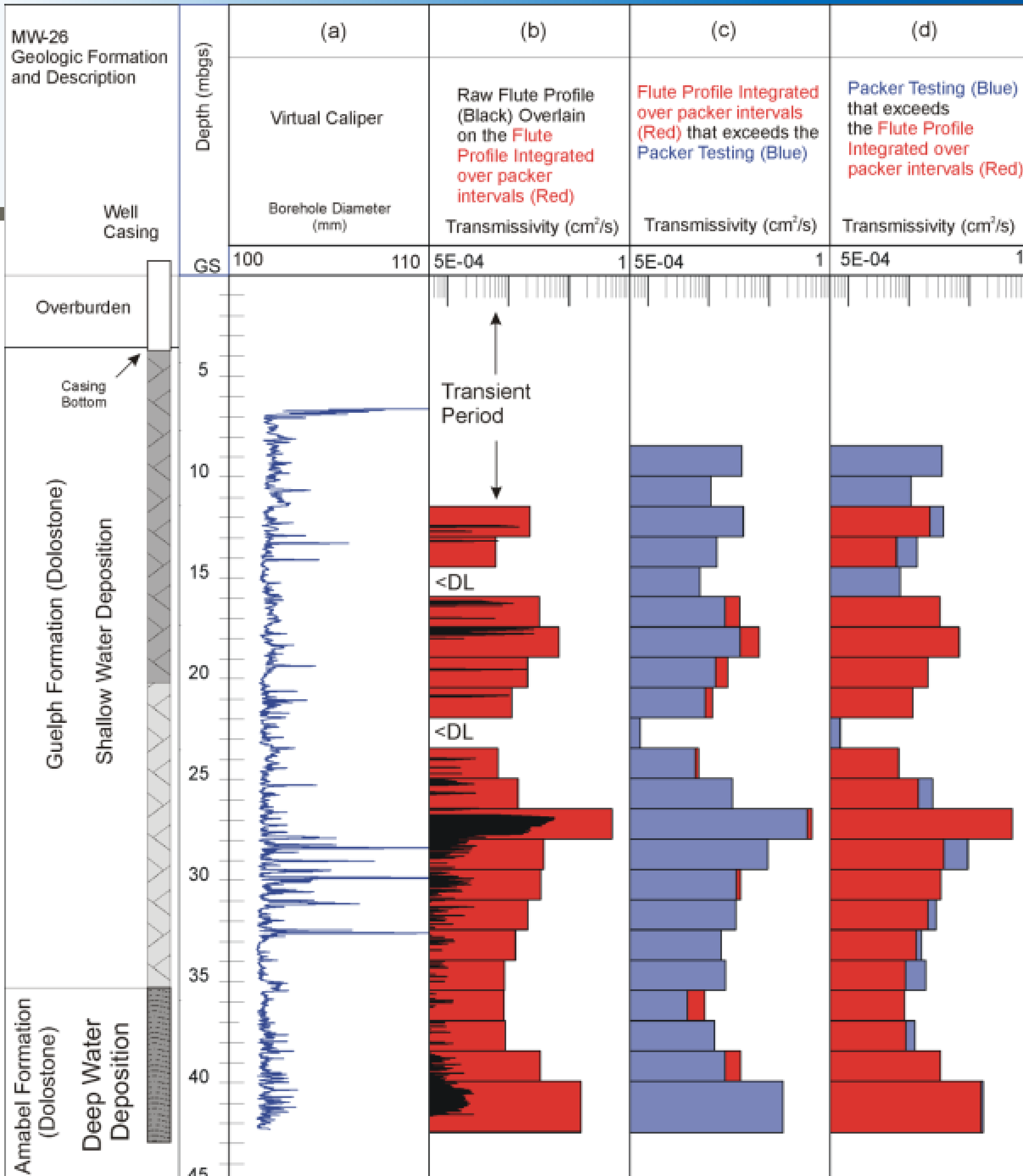
Cherry, Parker and Keller (2007) GWMR

Water FLUTe Installation K-Profiling



4-inch or larger diameter holes

Keller, Parker, Cherry
In submittal



Comparison between Flute Profiling and Packer Testing

Results are very similar

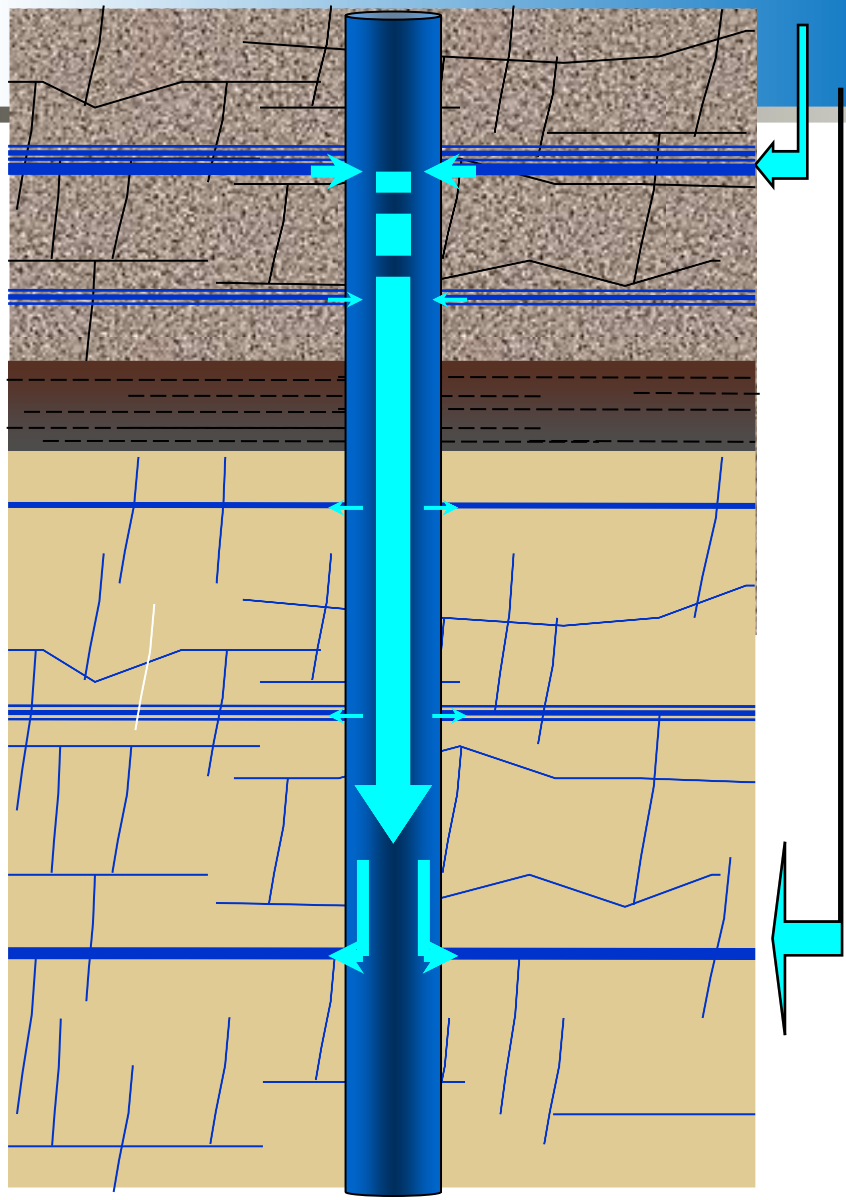
Keller, Parker, Cherry
In submittal

Identification of Transmissive Features - Hydraulic Testing

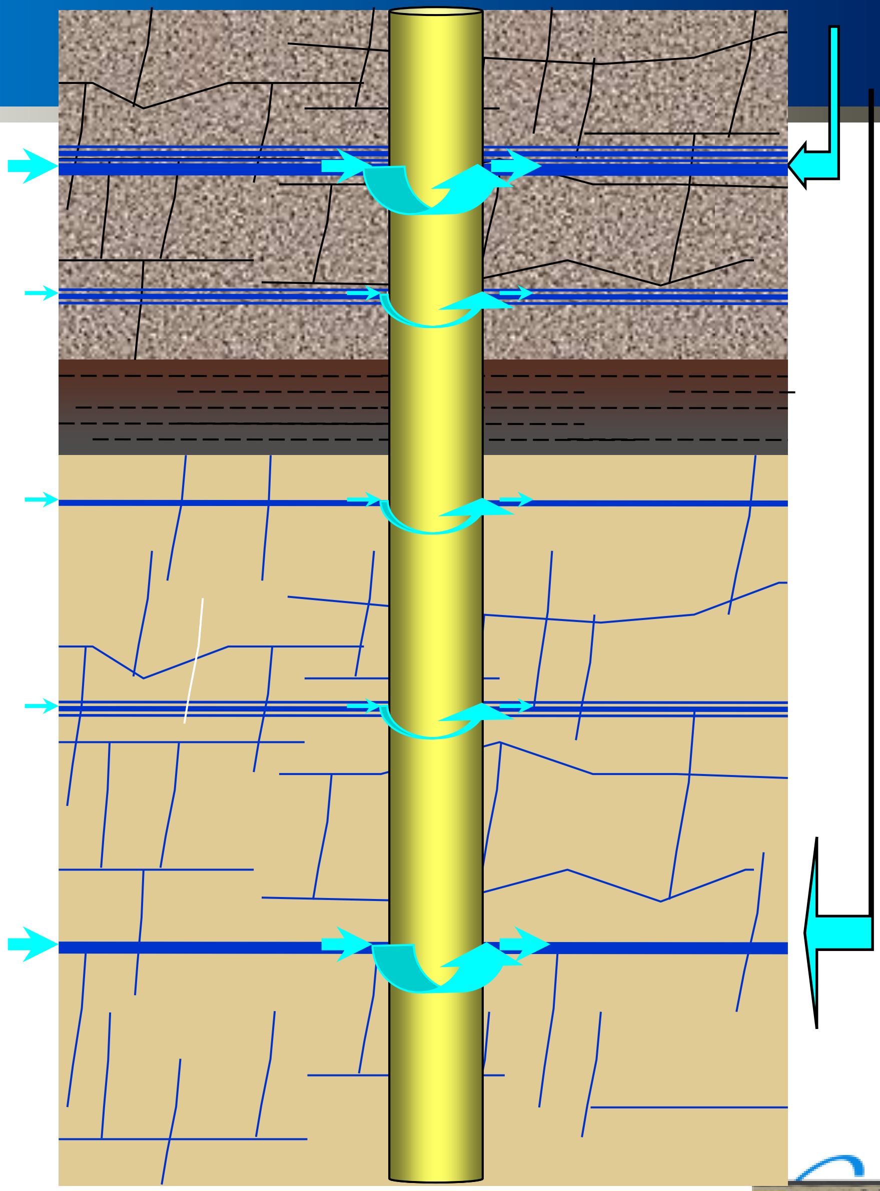
Three Types of Hydraulic Testing Methods:

1. High Resolution Packer Testing
2. FLUTe K-Profiling
3. Active Line Source Temperature Logging

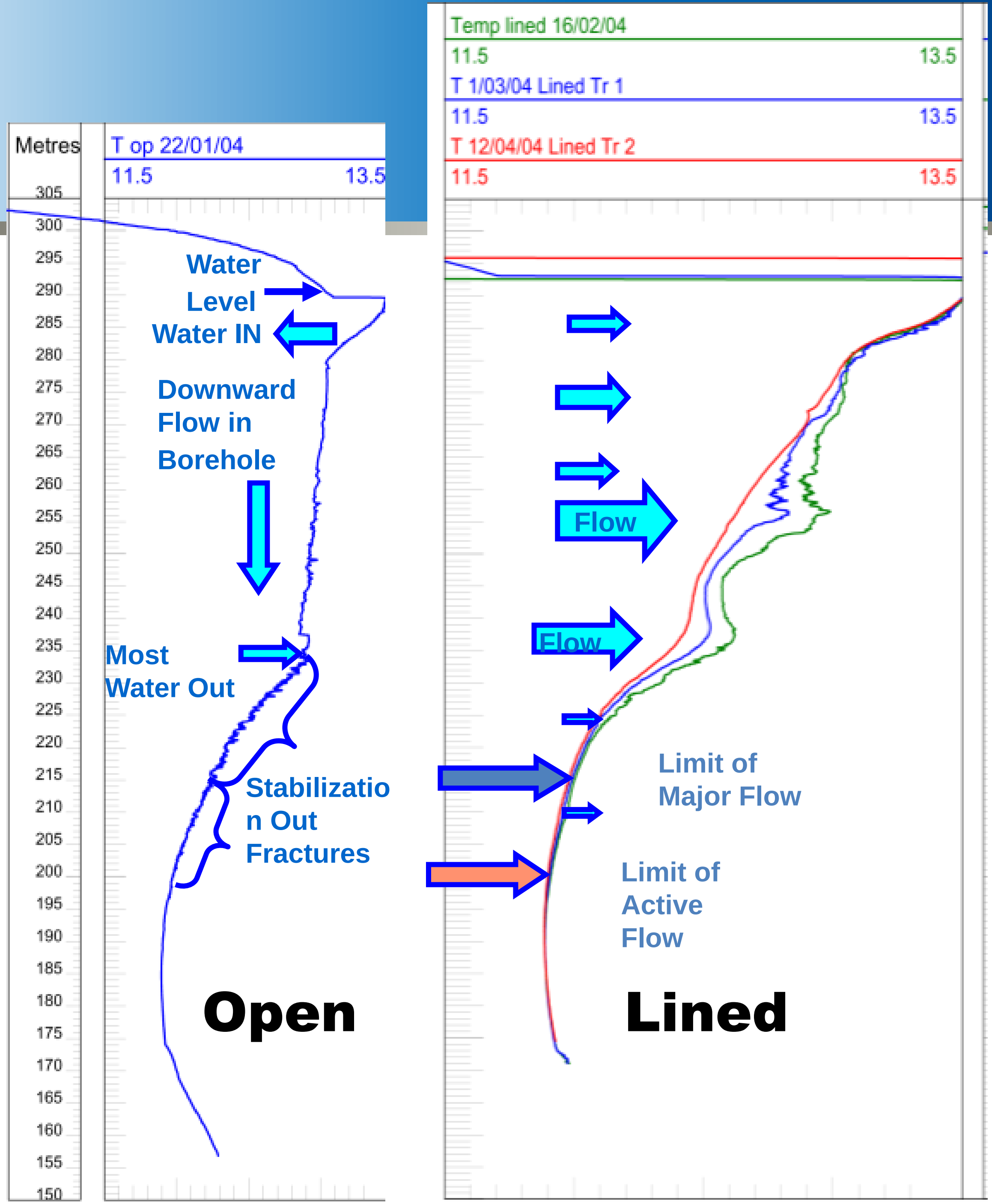
Cross-Connected



Not Cross-Connected



P.Pehme, 2006



Pehme et al. 2010

Active Line Source Temperature Logging

Pehme, PhD, 2012

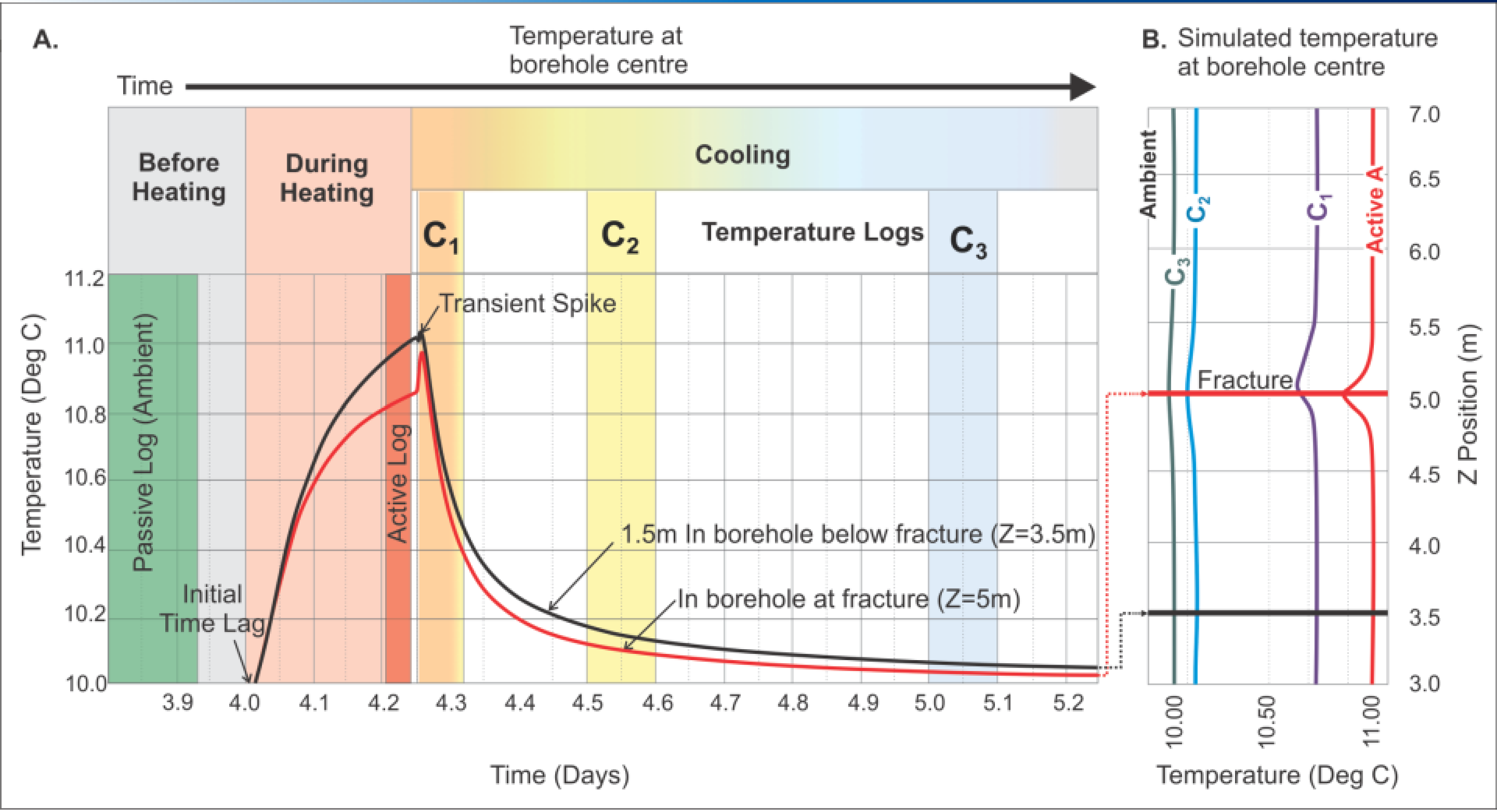
Innovative use of a FLUTe™ lined hole

Very sensitive temperature probe

Provides a *NEW* type of data



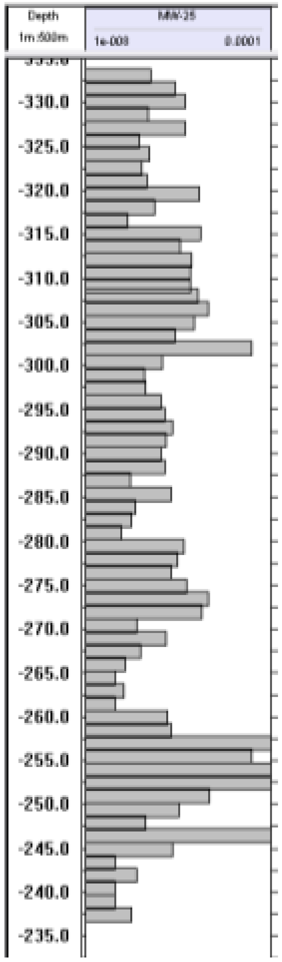
Simulated Probe Response at Fracture



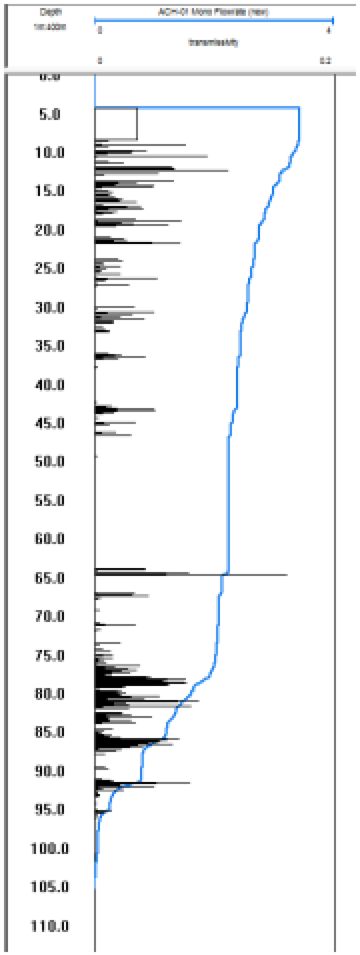
Pehme, PhD, 2012

Data Collection/Methods

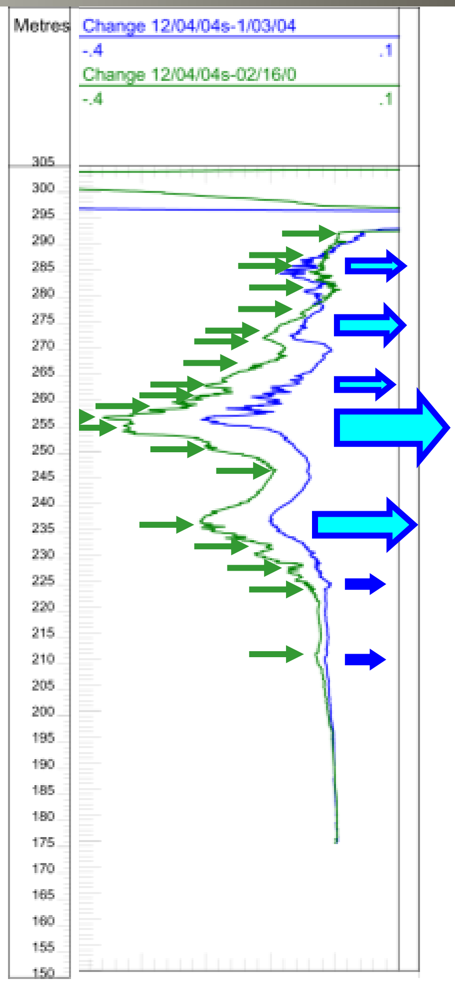
- **Example Results – Hydraulic Testing**



Packer Testing

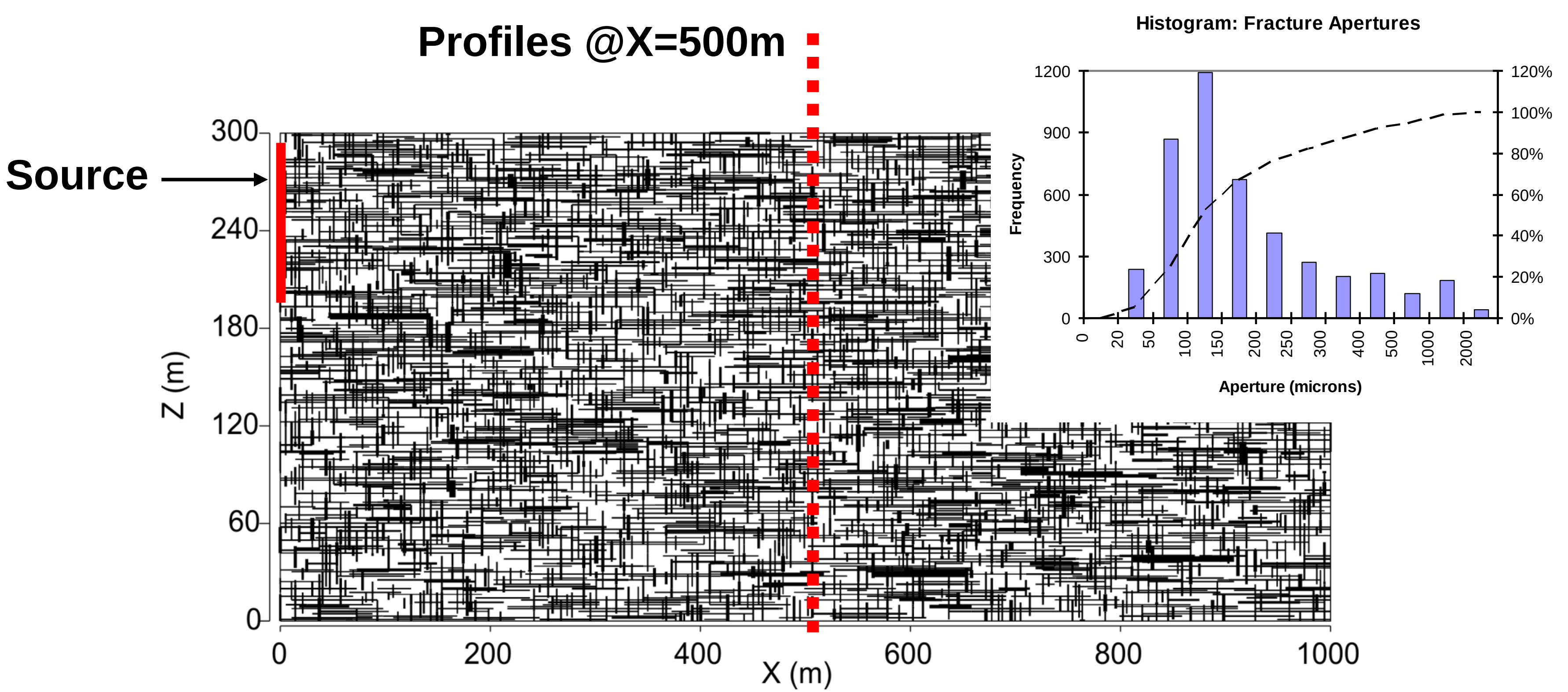


FLUTe Profiling



Temperature Logging
In FLUTe lined hole

Vertical Cross-Section
Well-Connected Fracture Network

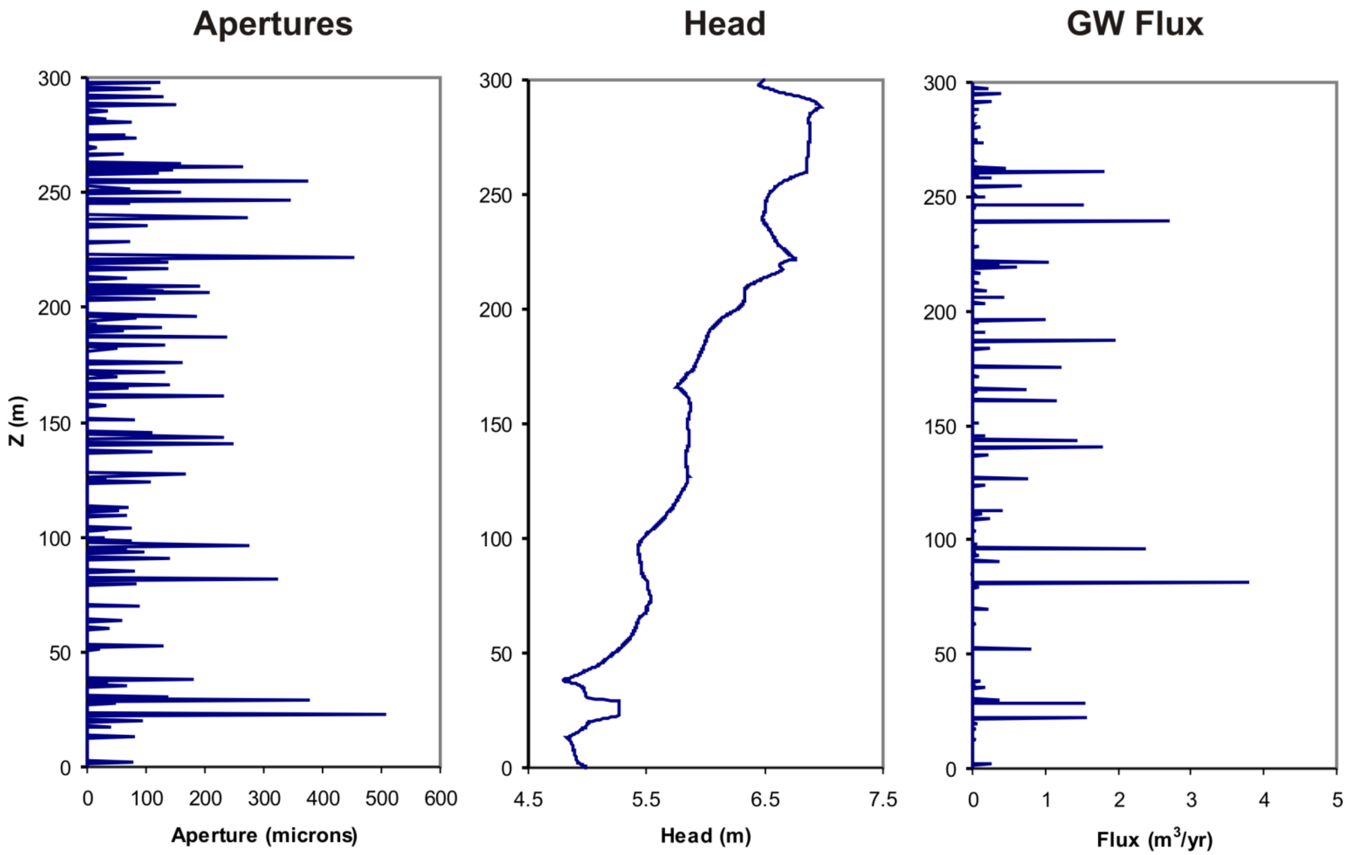


Geometric Mean Fracture Aperture = 100 microns
Horizontal Fracture Length Range = 20-100 m

# of fractures: Horiz=1700, Vert=2750 → Total = 4450

Vertical Profiles: X=500m
Well-Connected Fracture Network

Simulated Profiles



Overview of DFN Methods

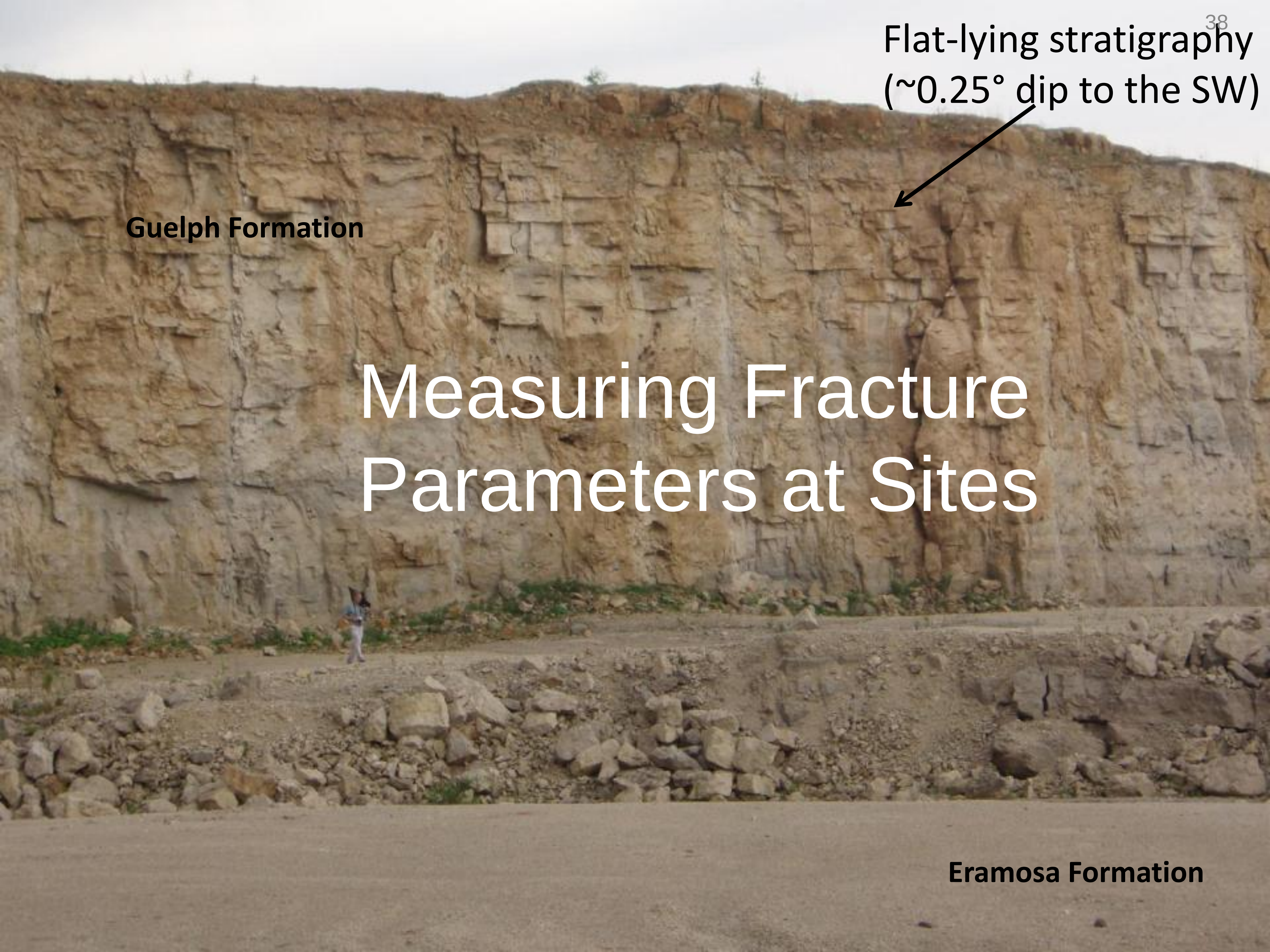
- Rock Core Chemical Analyses
- Improved Borehole Geophysics
- Improved Hydraulic Tests Using Straddle Packers
- Impermeable Flexible Liner (FLUTe™) Technologies

Forced Gradient (K or T)

- High Resolution Temperature Logging
- Passive Flux Meters

Natural Gradient (Flux)

- High Resolution Multilevel Systems
  - Characterization vs. Monitoring
- Static and Dynamic DFN Modeling (data integration)


Flat-lying stratigraphy
(~0.25° dip to the SW)
Guelph Formation
Measuring Fracture
Parameters at Sites
Eramosa Formation

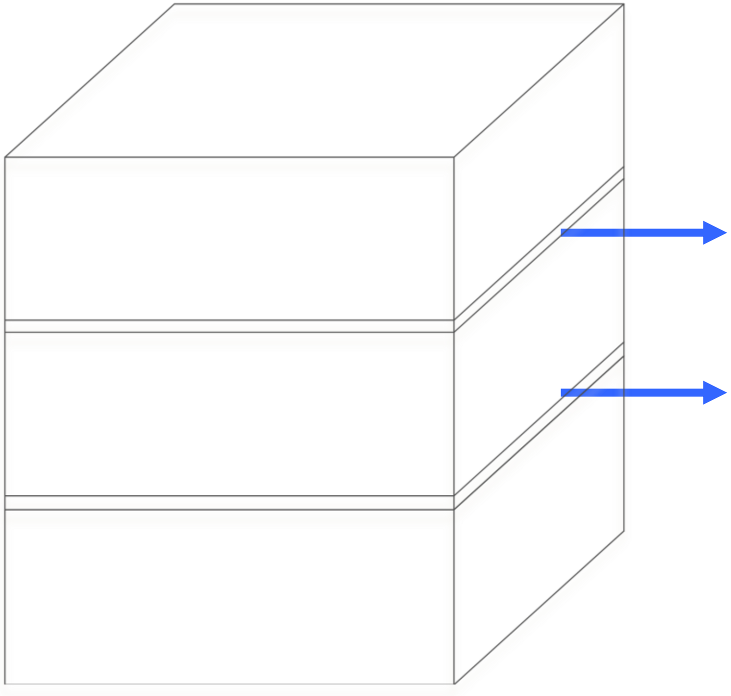
Hydraulic Fracture Apertures

HOW LARGE ARE FRACTURES?

We Need to obtain hydraulic aperture (2b) values

Use the Cubic Law

(Smooth, parallel-plate fractures)



$$2b = \left(\frac{12 \mu T}{\rho g \mathbf{N}} \right)^{\frac{1}{3}}$$

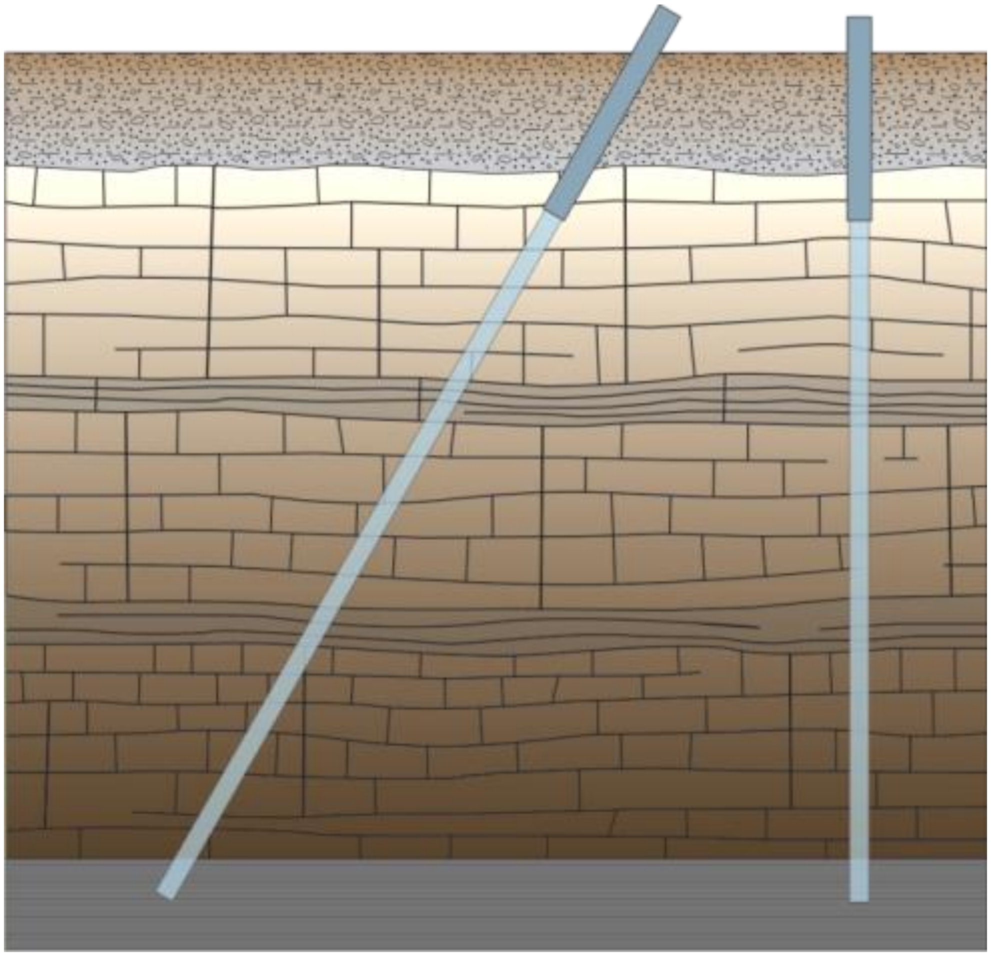
***N* = number of active fractures in the test interval**

***T* is bulk rock transmissivity determined from hydraulic tests**

Fracture Frequency and Network Geometry

HOW MANY FRACTURES ?

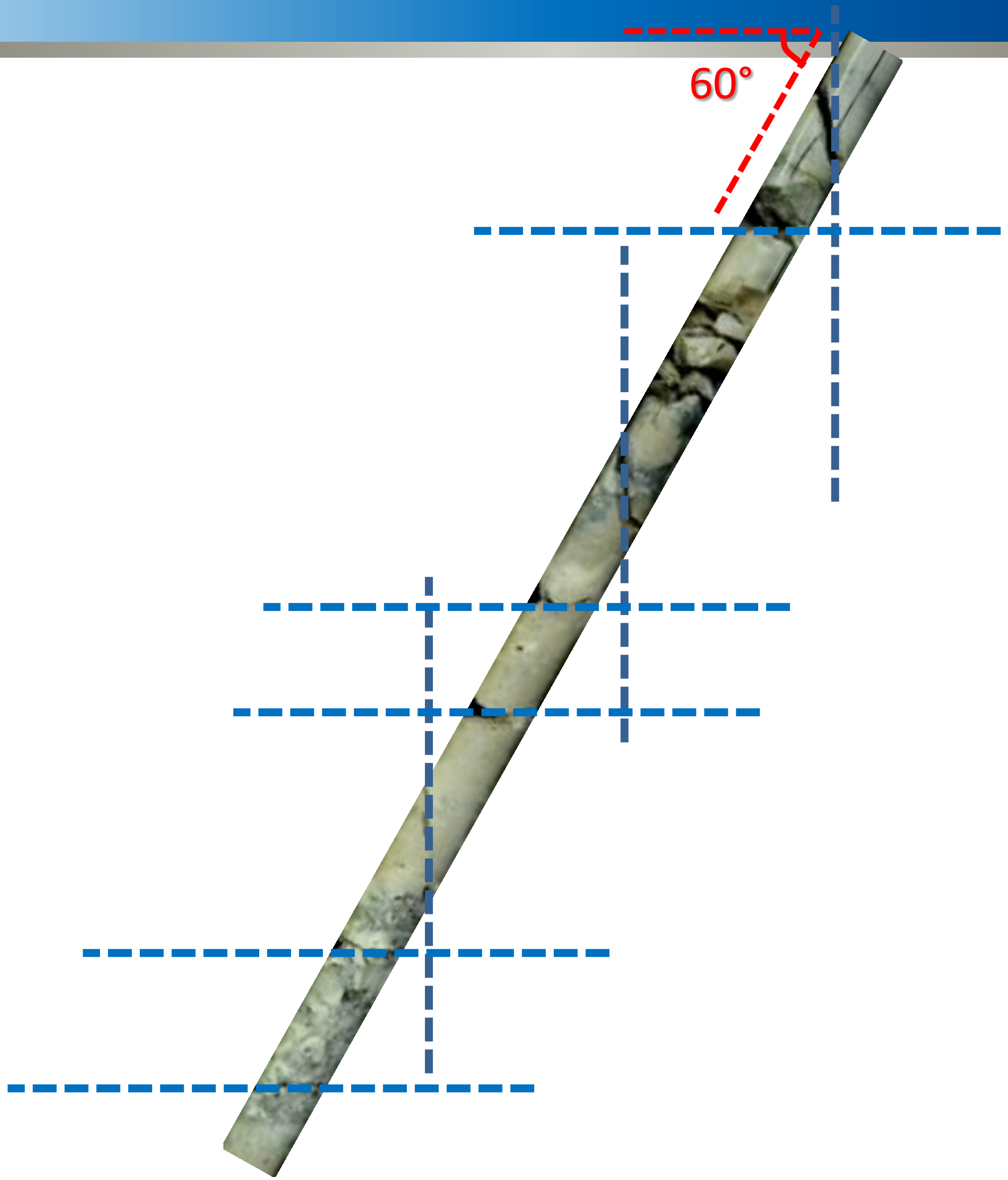
Inclined coreholes will reduce sampling bias



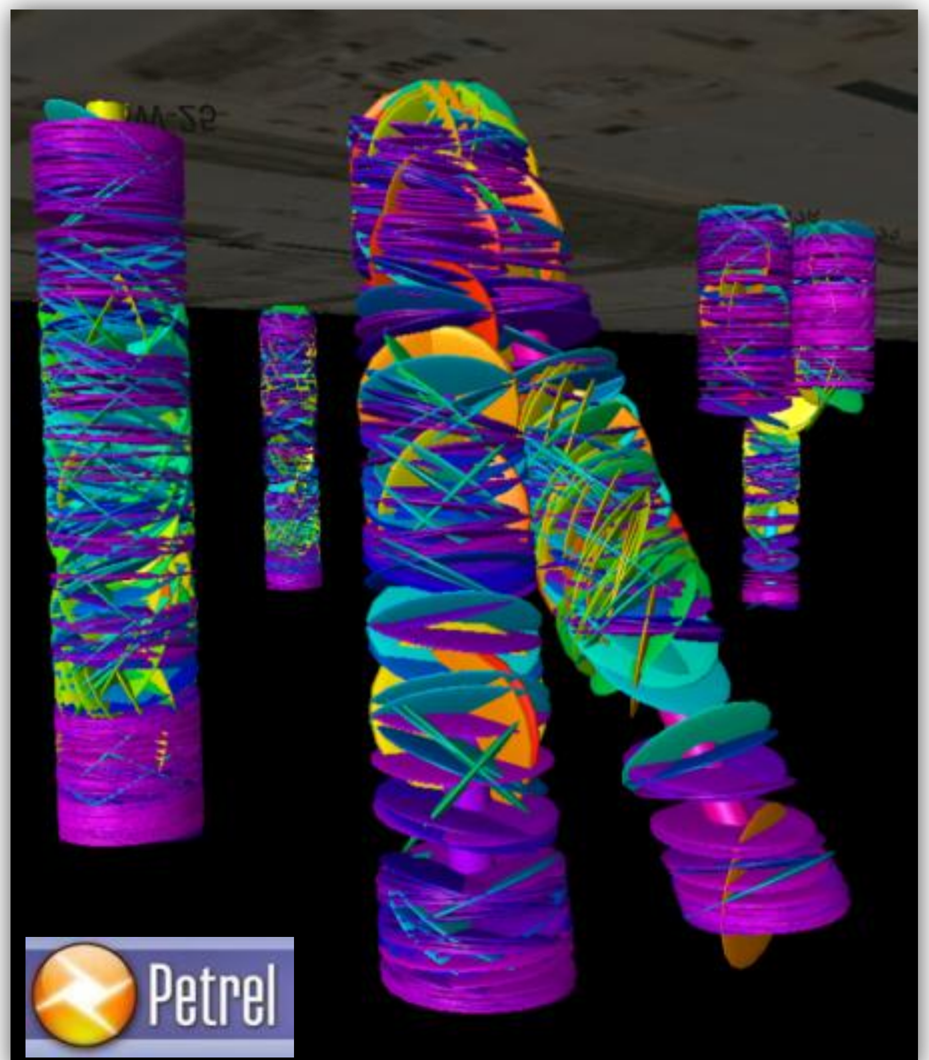
- Increase probability of intersecting high-angle fractures
- Commonly used in mineral exploration, mining, petroleum, and nuclear industries
- Not commonly used in environmental industry

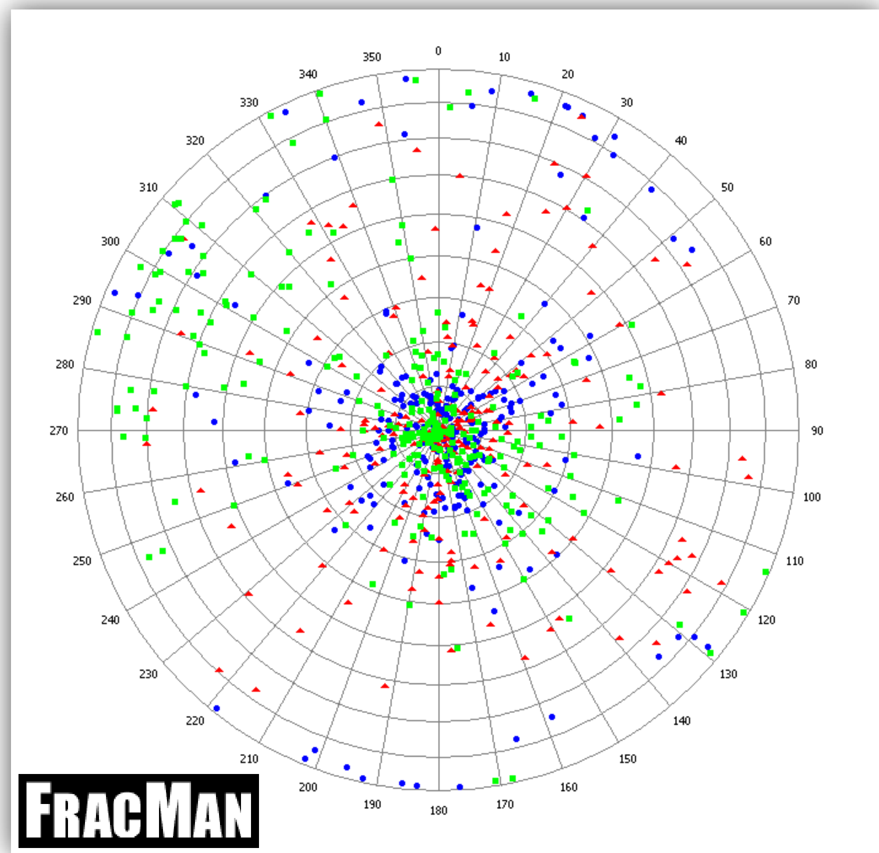
Munn, MSc, 2011

Vertical joints and bedding plane fractures



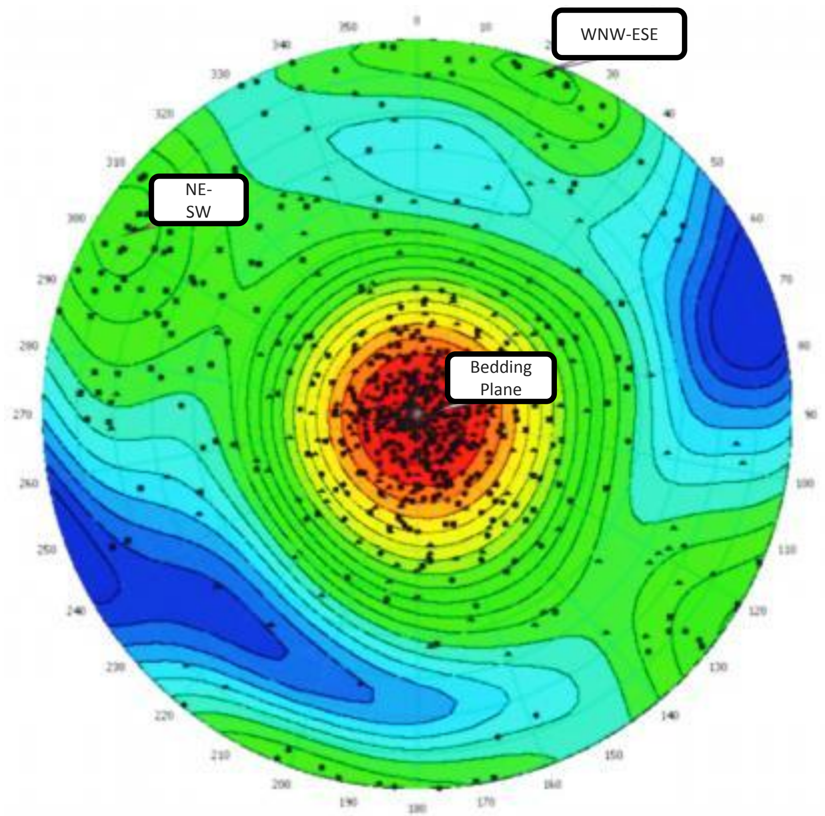
Orientated data allows accurate 3-D structural analysis





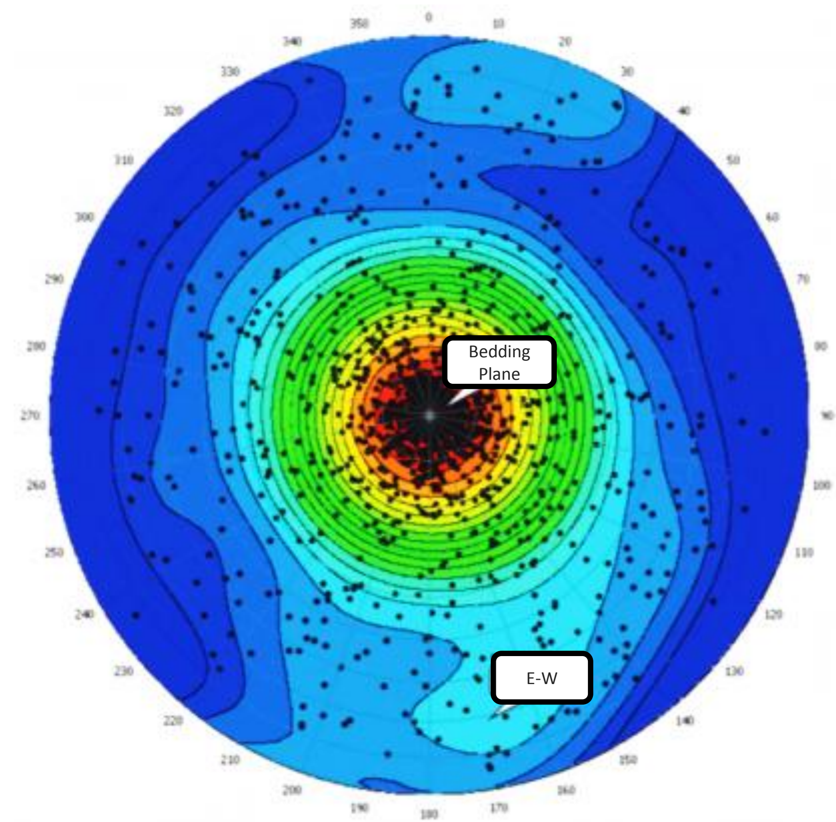
Analysis with inclined coreholes vs. only vertical coreholes

With inclined coreholes



74% bedding plane
26% High- angle

Only Vertical Coreholes



88% bedding plane
12% High- angle

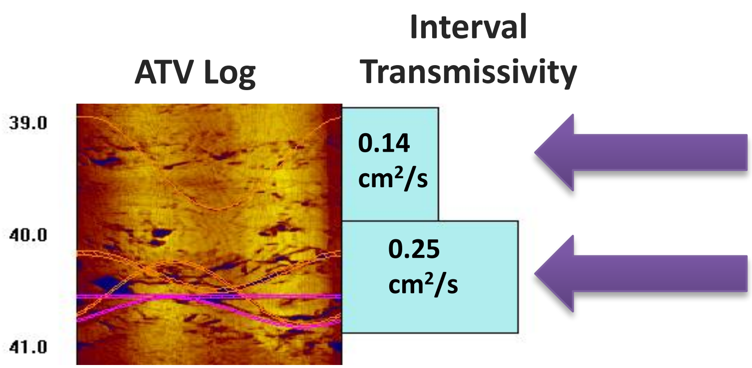
Munn, MSc, 2011

Hydraulic aperture calculations
Cubic Law

$$2b = \sqrt[3]{\frac{12\mu T}{\rho g N}}$$

2b = hydraulic aperture
μ = dynamic viscosity of water
ρ = density of water
g = acceleration due to gravity
T = transmissivity (FLUTe Profile)
N = number of fractures in interval
(Core or ATV Logs)

Example:

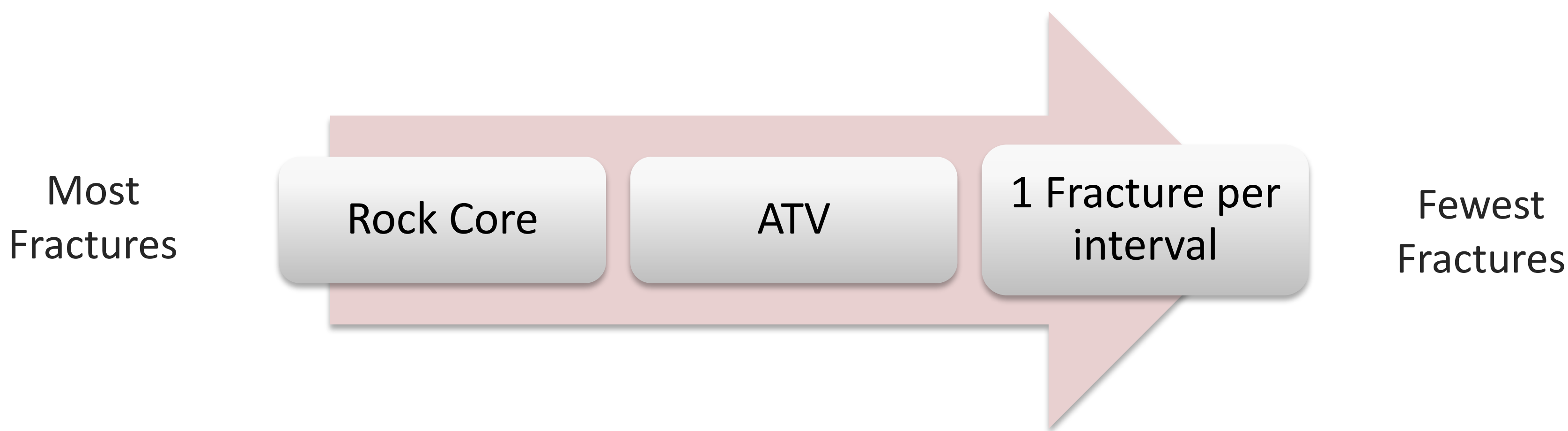


1 Fracture with an interval T of 0.14 cm^2/s
Average Hydraulic aperture: **281 microns**

4 Fractures with an interval T of 0.25 cm^2/s
Average Hydraulic aperture: **216 microns**

Three different fracture sources used to test sensitivity to number of fractures

- Rock Core
- ATV Image
- 1 fracture per interval (most conservative)



Munn, MSc, 2011

Hydraulic Aperture Distribution

- Overall, hydraulic aperture ranged from 15 to 407 microns
- Geometric mean aperture (using core data) was 125 microns
- Hydraulic aperture distributions show a moderate to strong positive skew
- Not highly sensitive to the number of fractures in the interval (likely due to the very small T-intervals)

	MW-25			ACH-01			ACH-02		
	Core	ATV	1 Frac.	Core	ATV	1 Frac.	Core	ATV	1 Frac.
Geometric mean	**147**	146	159	125	145	158	104	113	122
Mean	158	160	173	139	159	173	115	126	135
Minimum	**49**	49	49	39	50	61	15	19	19
Maximum	**407**	407	407	396	396	396	297	317	317
Count	108	95	81	338	231	189	244	178	152

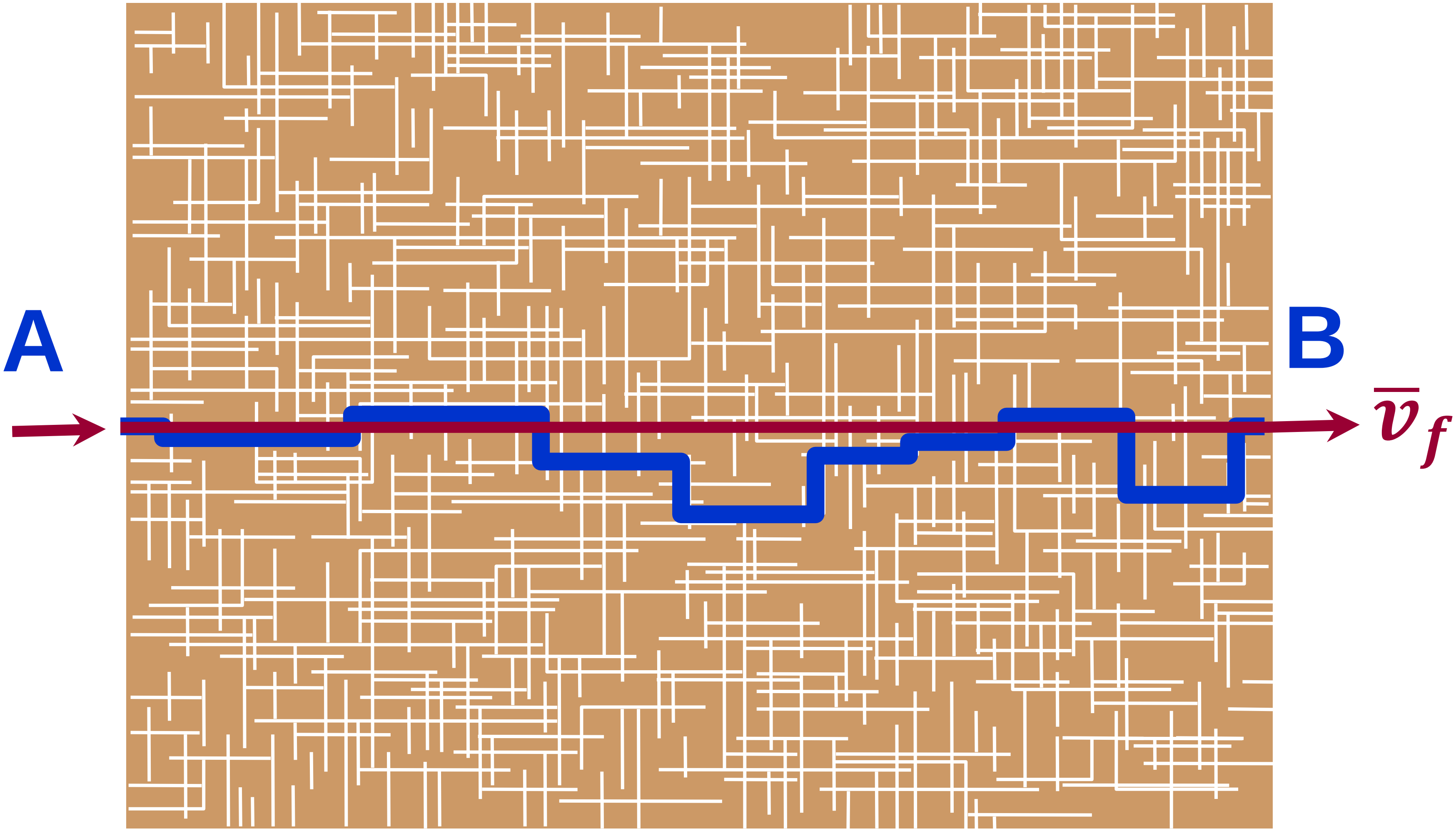
Munn, MSc, 2011

Groundwater & Contaminant Travel Times

WHY DO WE WANT TO KNOW ?

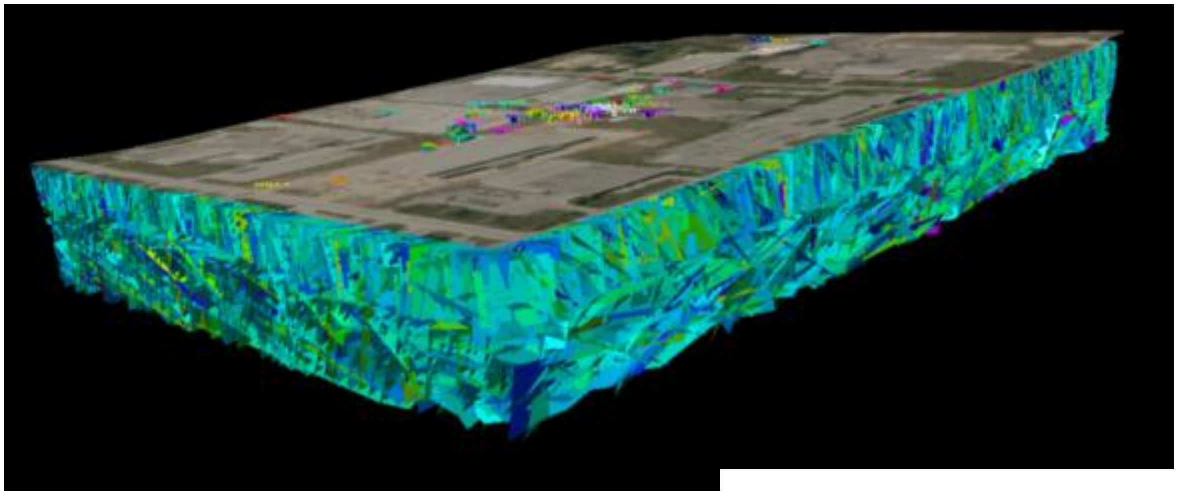
$$\bar{v}_f = \frac{K_b\, i}{\phi_f}$$

Average Linear Groundwater $(\bar{v})$ Velocity in Fractured Media

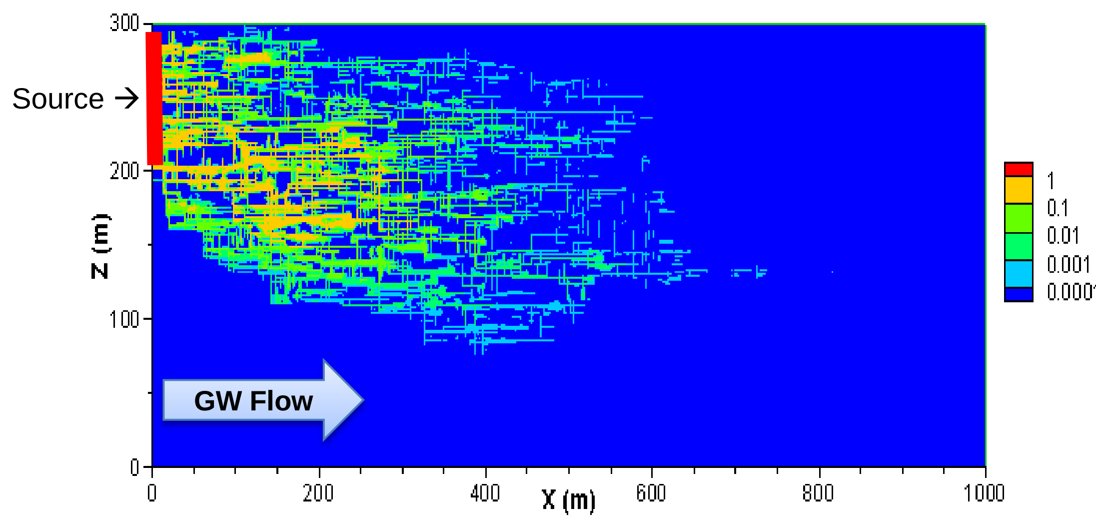


$\bar{v}_f$ represents line path from A to B

Application of Results

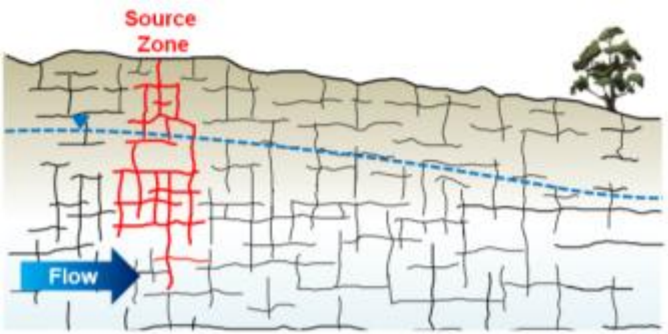


Results of study can be used as input parameters into static and dynamic models to assess current and future threats to municipal supply wells



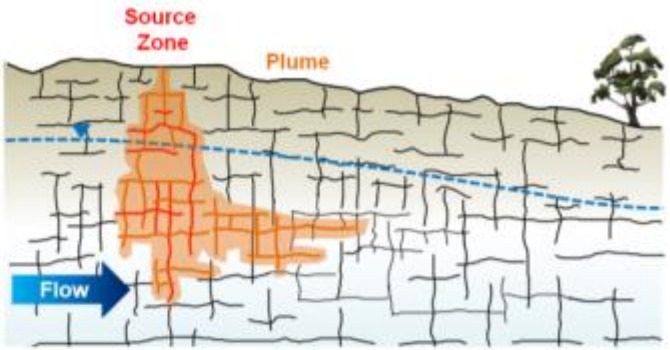
Source Zone / Plume Evolution Conceptual Model

Early Time



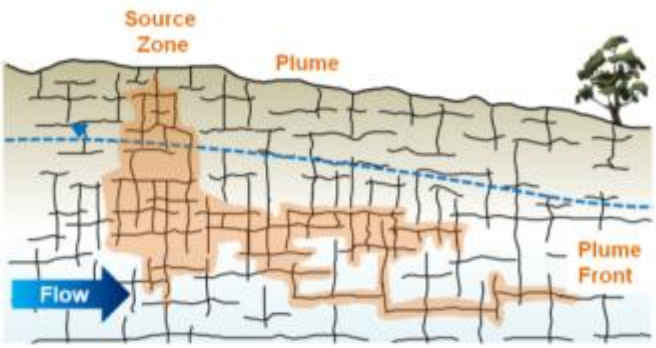
DNAPL reaches stationary phase in fractures

Intermediate Time



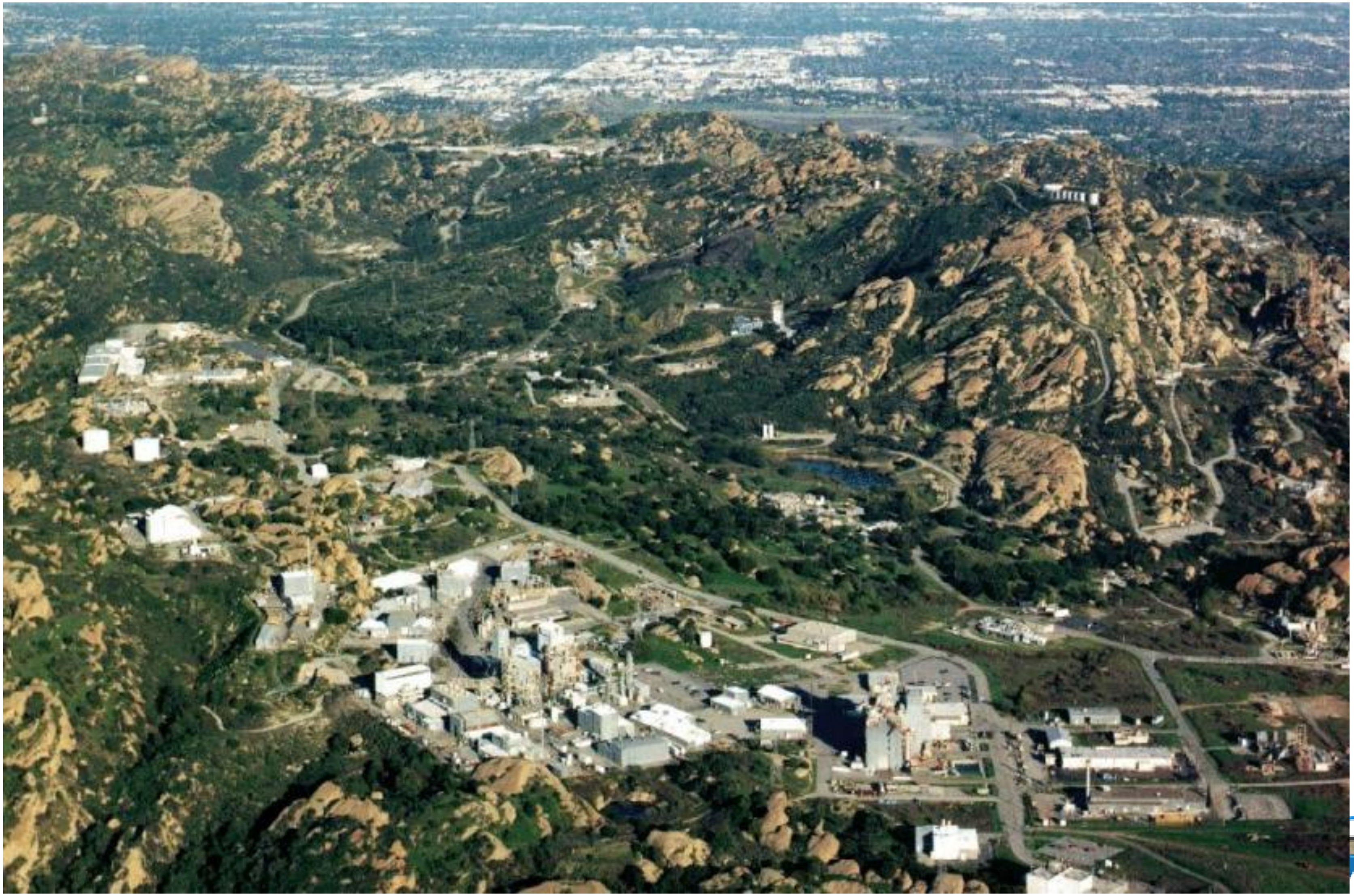
Much DNAPL disappeared, diffusion into matrix in source and plume zones

Late Time

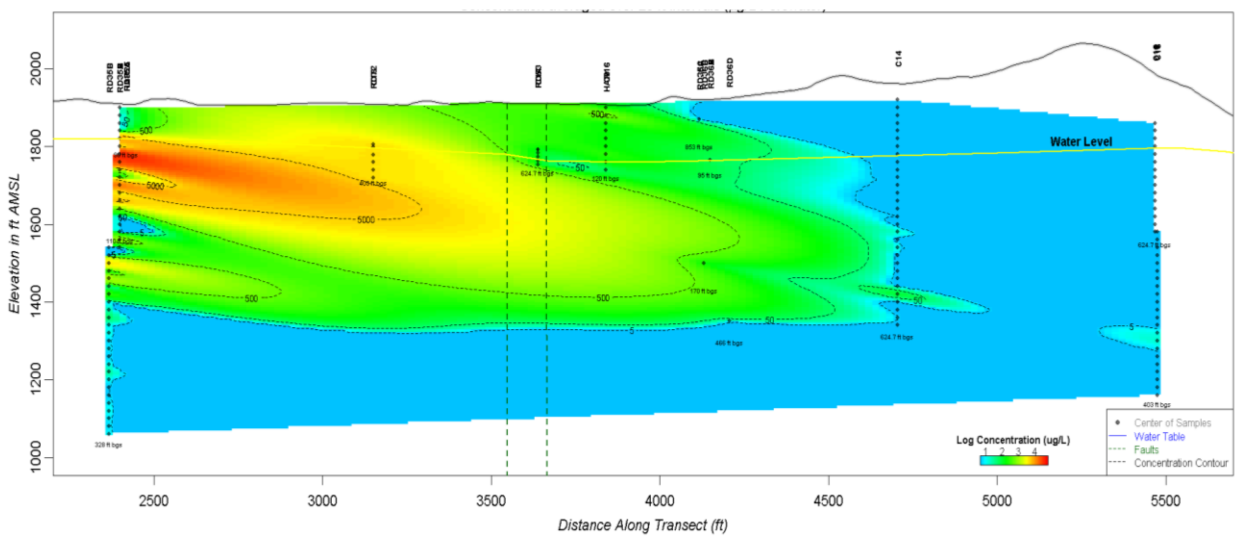


No DNAPL remains and most mass occurs in the matrix, diffusion and other processes cause strong plume attenuation

Case Study: California Site
Sandstone with shale interbeds, faults, etc.

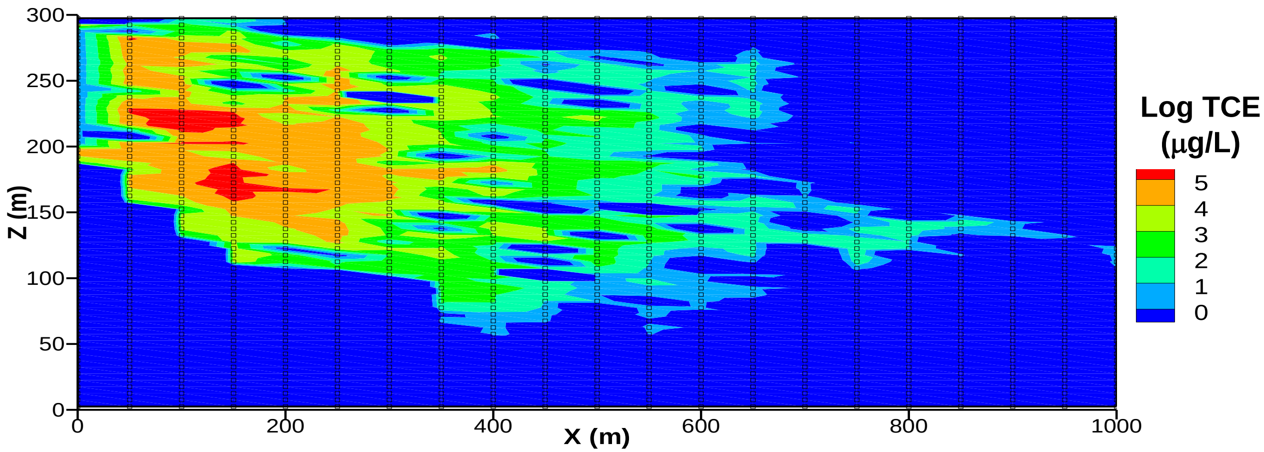


Comparison of FRACTRAN versus Field Results along Plume Longsect



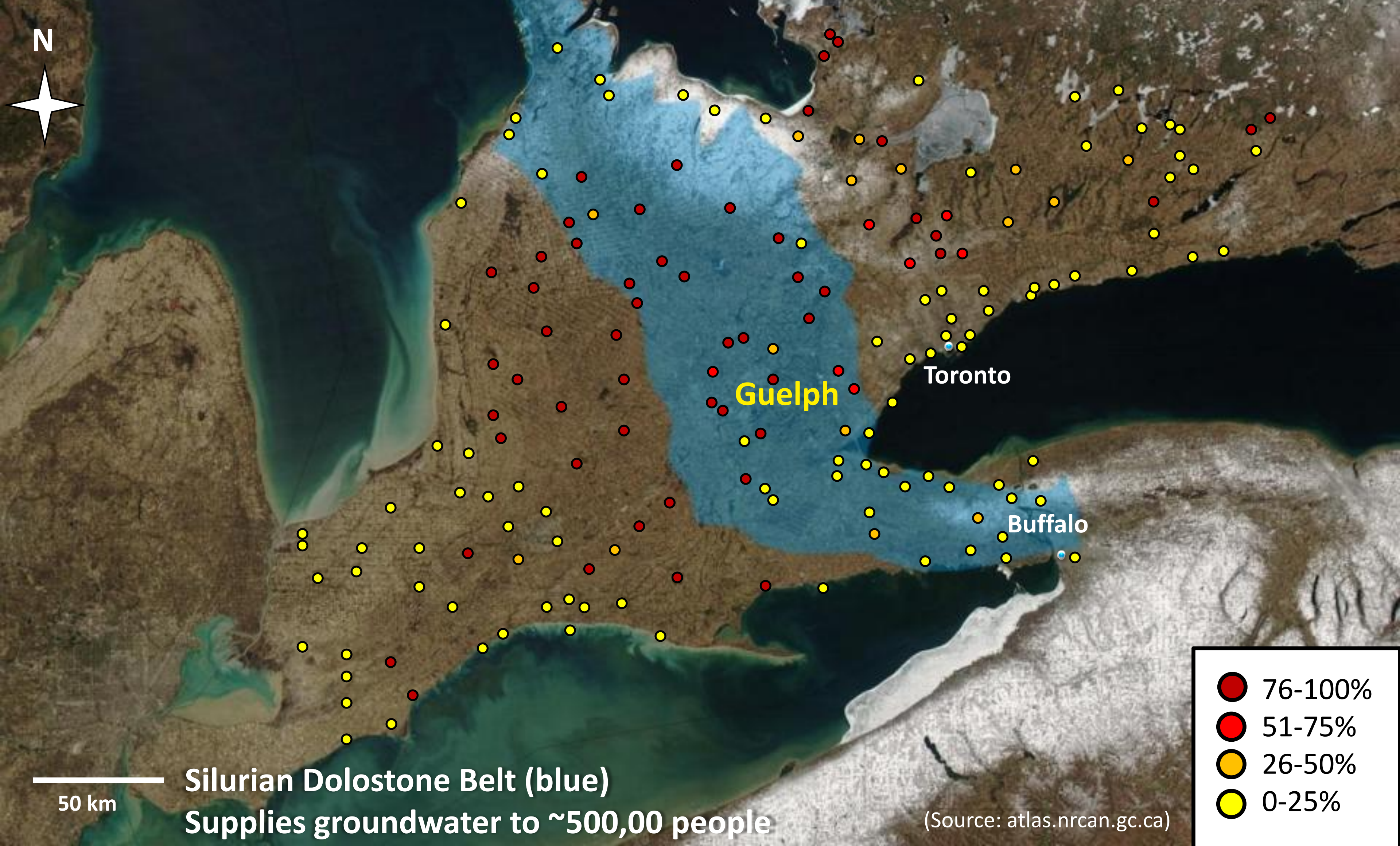
Field Plume Longsect (averaged)

FRACTRAN @ 60 yr (averaged)



Field and model show similar bulk plume style and extent

Percentage of Population Using Groundwater in Municipalities



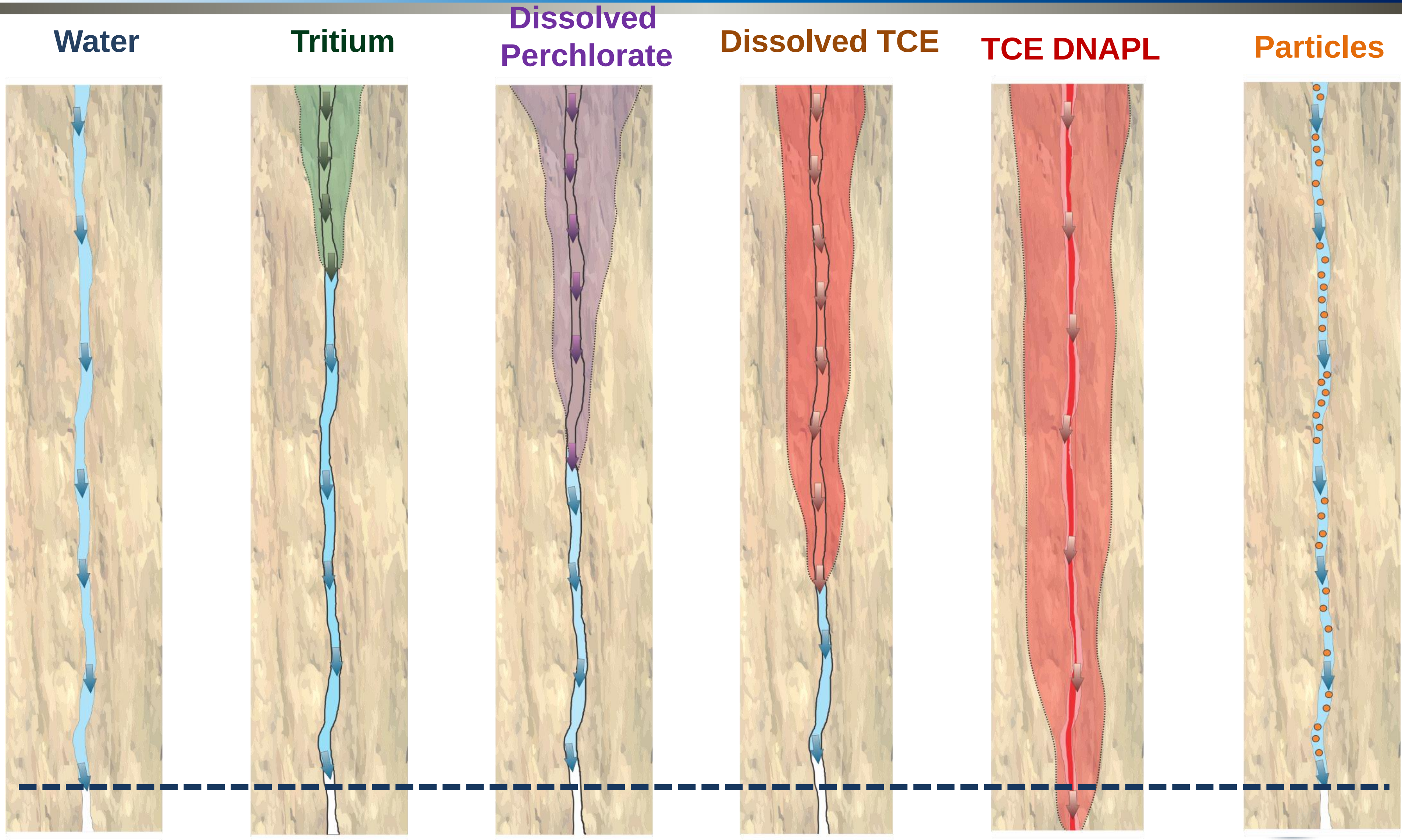
Silurian Dolostone Belt (blue)
Supplies groundwater to ~500,00 people

Nature of the Problem

(Photo: K. Belan)

- City of Guelph and many other communities rely on groundwater from bedrock aquifers
- Sources of contamination are common and have affected supply wells in Guelph
- Guelph's demand for water is increasing and the City is looking at reinstating decommissioned wells
- Need to understand contaminant migration through the aquifer

Retardation of Contaminants Due to Matrix Diffusion



Fracture Network Characterization Summary

- Many new and improved conventional methods exist –diverse tool kit
- Multiple data types can be used to calibrate and check for biases
  - Method performance is site & borehole specific
- Comparison and reconciliation of complementary data sets useful for refining site models and parameter inputs

Reduce uncertainty for improved decision-making

Discrete Fracture Network (DFN) Approach Characterization of Contaminated Bedrock

Initial Site Conceptual Model

Drill Corehole in and Near Contaminated Area

ROCK MATRIX

Use rock samples from continuous rock core for property measurements:

- Contaminants
- Physical
- Chemical
- Microbial

BOREHOLE

Use the borehole to acquire hydraulic data and water samples

Conceptual and mathematical modeling

Prepared by B.L. Parker

Discrete Fracture Network (DFN) Approach